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Abstract

The literature on model testing with a tail sting support is reviewed for its application to submarine experiments on the Marine Dynamic Test Facility (MDTF) proposed for the Institute for Marine Dynamics, St. John's, Newfoundland. A number of flow mechanisms for both static and dynamic sting interference are discussed in this context, but because of the unique features of the MDTF their relevance is not always clear. Other sting-related issues such as deflection under load and vibration are discussed briefly. It is concluded that sting support for large submarine models on the MDTF is feasible for acceptable levels of interference without elaborate correction procedures. Some recommendations are made for MDTF implementation.

Résumé

Les publications sur la mise à l'essai de modèles soutenus à l'arrière par une balance-dard ont été étudiées dans le but d'utiliser une balance-dard pour les essais de sous-marins sur l'installation d'essai de dynamique marine proposée por l'Institut de dynamique marine de St. John's Terre-Neuve. Plusiers mécanismes d'écoulement pour les interférences statiques et dynamiques de la balance-dard sont traités en fonction du contexte mais à cause des caractéristiques uniques de l'installation d'essai leur pertinence n'est pas toujours évidente. D'autres points se rapportant à la balance-dard comme la déformation sous la charge et la vibration sont traités brièvement. Il a été conclu que les grands modèles de sous-marins pouvaient être soutenus par une balance-dard sur l'installation d'essai et que les niveaux d'interférence étaient acceptables sans qu'il ne soit nécessaire d'effectuer desprocédures de correction élaborées. Certaines recommendations sont faites pour la mise en application sur l'installation d'essai.

Executive Summary

The Marine Dynamic Test Facility (MDTF) is a device for doing dynamic tests with models of submarines, submersibles, and surface vessels. It is a jointly-sponsored project of DND and NRC, and will be implemented at the Institute for Marine Dynamics (IMD) towing tank in St. John's, Newfoundland.

The innovative features of the MDTF include the use of a tail sting support for submarine and submersible testing. This arrangement clearly minimizes support interference on the measurements, but the necessity for, or degree of, correction required for the residual interference with the sting was initially unclear. This report reviews the relevant literature for sting interference in both static and dynamic model testing, and concludes that elaborate correction procedures are not required provided that some basic recommendations for the design and use of the sting support are followed.

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Nomenclature

$C_{D_{STING}}$	sting drag correction, Carter and Palliser's notation [43]
$Cm_q + Cm_{\dot{\alpha}}$	lumped pitch damping coefficient
C_p	pressure coefficient
D_B	base, or body, diameter
D_M	maximum body diameter
D_S	sting flare, or support, diameter
d	model diameter (Wehrend's notation — see Figure 18)
d_s	sting diameter
K_2, K_3	coefficients in Viswanath and Rajendra's afterbody drag correction
L_S	sting flare, or support, length
ℓ_s	sting length
l	model length (Wehrend's notation — see Figure 18)
M	Mach number
p	roll about the MDTF sting axis
r^*	Rossby number characteristic length; see Section 3.3
U	towing carriage forward speed
U_{LOCAL}	local flow speed in direction of carriage motion
u'	nondimensional axial velocity
Δu	surge correction imposed by actuator in MDTF beam assembly
V_1, V_2	lateral velocity of forward and aft MDTF subcarriages
W	Rossby number characteristic velocity; see Section 3.3
W_1, W_2	vertical velocity of forward and aft MDTF struts
X'_{aft}	afterbody drag coefficient
x	axial distance
α	angle of incidence
β	afterbody boat-tail angle; also drift angle
β_{LOCAL}	local drift angle
θ	flare half-angle
θ_s	sting taper half-angle
Ω	Rossby number characteristic angular rate; see Section 3.3

1 Introduction

1.1 Background

Captive model testing in a towing tank, wind tunnel, or similar facility, requires a means of supporting the model so that it has a known attitude with respect to the incident flow (static testing), or moves through a prescribed trajectory (dynamic testing). Ideally, the support is unaffected by model weight, buoyancy, or the fluid dynamic forces imposed on the model, and should have no influence on the measurements and observations. These two requirements are contradictory: the former implies a massive, stiff model support while the latter implies a vanishingly small one. The various solutions (struts, swords, stings, and so on) to this problem are reviewed in the classic texts on model testing, such as Pope [1].

A tail sting support is required for model submarine testing on the Marine Dynamic Test Facility (MDTF) [2,3] proposed for the 200 metre Clearwater Towing Tank of the Institute for Marine Dynamics (IMD), St. John's, Newfoundland. This document summarizes a literature review of sting fluid dynamic interference and its implications for the MDTF. It may also have relevance for other applications. Discussion is generally restricted to the various mechanisms giving rise to interference, and to their prediction and alleviation, but some other issues, such as structural stiffness, are briefly considered in light of the requirement for a tail sting support.

Support interference is that part of an experimental measurement which is attributable to the method of supporting the model under test. Experimenters in fluid dynamics have long complained, with good reason, that it is a poorly understood and often ignored problem, as the following quotations suggest:

> Information ... shows that sting-support interference is considerable, but adequate information for the design of interference-free sting-support systems is lacking.
> *G. Lee and J.L. Summers, 1957* [4]

> The high accuracy of the basic measurements is difficult to match in measurements of the support interference and in the evaluation of corrections for tunnel constraint and model distortion.
> *C.R. Taylor et al, 1969* [5]

> Support interference results, ... are easy to misinterpret. Without additional experiments and careful analysis, the results tell next to nothing about the total support interference of either ... support system used.
> *L.E. Ericsson, 1990* [6]

The last source asserts that the situation persists for dynamic testing:

> Unlike the case of static tests, where it is common practice to conduct extensive calibration of the effects of wall and support interference on the aerodynamic measurements, there is little evidence of similar diligence in previous unsteady testing.
> *L.E. Ericsson, 1990* [6]

The starting point for this review was the bibliographies of support interference by Tuttle and Gloss [7], and Tuttle and Lawing [8]. Together, these comprise 176 abstracts from reports and articles which discuss interference attributable to all forms of support arrangements. The criteria for applicability to the MDTF included some form of sting support, subsonic flow, models which could be related to submarine configurations, and, where possible, dynamic effects. Applying these criteria revealed surprisingly few relevant references. A subsequent search of the open literature supplied some more, notably some of Ericsson's later work [6,9] and Mabey *et al* [10], but much of the work in this area has features which clearly do not apply to the MDTF. Unless it had particular merit, such a source was excluded from further consideration, and most references cited here adhere reasonably closely to the criteria listed above. Exceptions include, for example, studies performed in near-transonic flow ($M \approx 0.6$) where it is indicated that extrapolation to lower Mach numbers should not invalidate the conclusions [11].

Static and dynamic interference are discussed separately in terms of their principal mechanisms and effects as identified in the source references. Nevertheless, any classification of interference is really one of convenience, since in practice more than one interference mechanism is invariably at work, and each influences the other. Even the distinction between static and dynamic interference is artificial because the fundamental causes are, with few exceptions, no different.

1.2 The MDTF

Support interference is not present for surface vessel tests in the towing tank because the working section of the tank stops at the free surface, and the model support is entirely above it. Testing submerged vehicles, on the other hand, is analogous to wind tunnel experiments in which the support is in the flow field (we exclude half-model testing [1,12], which imposes restrictions on model and flow symmetry, and magnetic levitation, which is possible for only very small models [13,14]). Dynamic testing with submarine models on the MDTF presents a number of particular problems. A tail sting was selected as the principal support for submarine dynamic testing because of unacceptable interference from the more conventional twin-sword arrangement in the case of lateral motion. The price paid for this choice includes a more restricted kinematic envelope and lower stiffness and natural frequency [2].

The proposed MDTF general arrangement for submarine testing is sketched in Figure 1. It is shown installed in the 3×8 metre test frame of the IMD towing carriage. Motion in all six degrees of freedom is imparted to the model by hydraulically-driven ballscrew jacks which provide lateral motion (V_1,V_2) to the subcarriages and vertical motion (W_1,W_2) to the vertical strut assemblies, and by roll (p) and surge (Δu) actuators in the beam joining the bottom of the struts and terminating in the model support sting. All motions are independent and under computer control. Amplitudes and rates are large: up to ± 1 metre and ± 1 m/s; see Table 1 of Reference [2]. Alternative support arrangements are possible; for example, propulsion experiments can be done with motion in the vertical plane only, using twin swords.

1.3 Testing Submarine Models on a Sting

1.3.1 General Experience

There are few precedents for testing submarine models on a sting. Although widely used in aeronautical testing, sting-mounted models are usually small to reduce loads and vibrations, whereas the Reynolds number requirements for submarine model testing [15] lead to models which are typically several metres long.

A quadrant-supported sting was used by Kaplan [16], Reed [17], and others, for flow-field measurements with small models in the MIT Marine Hydrodynamics Laboratory variable pressure water tunnel. The sting provided the opportunity to make relatively interference-free LDV measurements in the flow field. Johnson [18] motorized the quadrant in order to perform coning experiments on a similar model equipped with an internal balance. Because of high tunnel blockage, the work was transferred to the towing carriage of the Davidson Laboratory High Speed Test Basin [19]. The same model, short sting, and quadrant were used as before.

Iitaka [20] conducted tests with submersible models between 0.8 and 1.2 metres long in a 1.2 metre deep water tunnel. His apparatus was a modified single-strut Planar Motion Mechanism (PMM) on which the strut could support a sting for static tests or for dynamic roll or surge. Dynamic pitch, heave, sway, and yaw had to be done with the strut directly supporting the model, presumably because of inadequate sting stiffness. Figure 2 illustrates this device in the sting support mode (upper part of the figure), and strut support mode (lower part, streamwise view). Surge tests on the sting were done at amplitudes up to ± 50 mm and roll tests at amplitudes up to ± 20 degrees, both at frequencies up to 1 Hz.

Motter [21] provides a brief description of the new sting support arrangement for the CDNSWC (formerly DTRC) rotating arm, see Figure 3. It is used for static tests with the model set at an angle of roll, pitch, or yaw. The sting and strut were designed to a maximum angular deflection under load of 0.2 degrees at the model. The sting has a conical reduction where it enters the model, presumably to minimize model truncation and modification (discussed in Section 2.4), but this can be expected to give unfavourable blockage effects as noted in Section 2.2.1.

Ward and Wilson [22] used a combined sting/forward strut support for afterbody separation studies in the DRA Haslar Circulating Water Channel. As required, this arrangement provided relatively interference-free flow on the hull aft of the sail, but it is clear that most of the loads were carried by the forward strut, and that the sting was a secondary element.

Wetzel and Simpson [23] used a tail sting support for force and flow visualization experiments on a model approximating the 688 class in the Virginia Polytechnic Institute and State University Stability Wind Tunnel. Not many details of the support arrangement are given, but it appears that the sting diameter was about 50 percent of hull diameter, and that the aft end of the model was truncated at 89 percent of hull length. Aft appendages were omitted.

1.3.2 DREA Experience

DREA has used sting support systems in a number of wind tunnel static experiments. In testing models from the Canada/Netherlands submarine systematic series in the Institute for Aerospace Research (IAR) 2 × 3 metre wind tunnel, sting mounting was initially adopted to minimize support interference in flow visualization experiments [24]. In this tunnel, a strut from the under-floor balance, shielded by a fairing aligned with the flow, supports the sting at the centerline of the working section, Figure 4. Subsequently, the same arrangement was used for making balance and static pressure measurements in afterbody separation studies with these models. A truncated submarine afterbody with rudders and sternplanes corresponding to a larger model was also tested on this sting.

A similar arrangement has been used for the DREA Static Test Rig (STR) in the IAR 9 × 9 metre wind tunnel [25,26]. In this facility, the sting support is employed in the procedure for tare and interference corrections, and for flow visualization, wake surveys, and other experiments which might be compromised by struts entering the hull. Since both IAR tunnels use external balances, tares are generated by the exposed sting and strut components; these tares have to be removed from the measurements. Figure 5 shows two versions of the STR sting support. In the original arrangement, Figure 5a, an extension to the strut fairing shielded only the upper strut and part of the sting (this picture also shows the wake survey rig in place aft of the model). A module for rotating the model was subsequently added, Figure 5b, and the module and most of the sting are enclosed in a fairing which further reduces tares but may increase interference because of its greater bulk. Work is underway to equip the STR with an internal balance which will eliminate tares altogether.

The sting supports are not optimal in either facility; this results from the use of existing arrangements and from the stiffness and strength requirements associated with medium and large wind tunnel models. The size and proximity of the struts supporting these stings (Figures 4 and 5) suggest that there is significant downstream blockage (Section 2.2.1) in both cases. Models were unavoidably truncated, and those in the 2 × 3 metre tunnel were also modified slightly to conform to the sting, see Figure 4b. Where possible, corrections have been made to the data, more rigorously in the case of the STR. Comparison with measurements made using a twin-sword support in the Maritime Research Institute Netherlands (MARIN) towing tanks is generally quite favourable, see Figure 6, despite other differences (such as Reynolds number) in the test conditions.

In June 1992, a small sting-supported submarine model was tested on the high incidence rig in the 2D working section of the IAR 1.5 metre blowdown wind tunnel [27]. This arrangement is typical of the classic setup for high-α aerodynamic testing, see Figure 7. The sting/hull diameter ratio in these tests was the same as that of the STR, but downstream blockage is lower in the blowdown tunnel.

Static frame evaluation tests of the pilot model MDTF used a 2 metre long sting-mounted model [3]; the rig is sketched in Figure 8. The sting consists of a parallel section 2.75 diameters long (sting diameter is equal to 25 percent of model diameter), followed by a 1.2 degree tapered section almost 7 diameters long. This should have provided stiffness within specifications, but excessive deflections and a low first natural frequency were observed. The cause of the problem,

and a solution, appear to be straightforward, and are summarized in Appendix A. It will not be necessary to modify the rig for evaluation tests at IMD.

The actual MDTF will most likely standardize on a model length between 4 and 6 metres, and the sting dimensions will be increased accordingly. Other modifications to the model support arrangements will include streamlining the vertical struts and modifications to the beam joining the bottom of the struts. It is hoped that this review will provide background information and guidance for MDTF sting and beam redesign.

2 Static Sting Interference

2.1 Overview

In discussing static sting interference, it is convenient to adopt the classification of Britcher *et al* [13,14] which recognizes three components: overall interference, local interference, and interference arising from modifications to the model. These three components are illustrated in Figure 9. Reference [14] observes that the first, overall interference, is usually minimized by "correct" support design, and can be corrected for experimentally or numerically, whereas traditional correction methods may not be valid for local interference and model modifications.

2.2 Overall Sting Interference

This is interference attributable to a disturbance of the overall flow, such as downstream blockage which may arise from the sting or its supporting structure. Although considered here (as in most of the literature) in the context of static measurements, there are generally analogues in dynamic testing which could be addressed by equivalent unsteady analysis.

2.2.1 Downstream Blockage

The effect of blockage is expressed in various rules-of-thumb which define the distance between the model and the sting support in terms of some combination of model, sting, and support dimensions. Downstream blockage results in a longitudinal velocity gradient which will influence the aft end of the model. In a submarine experiment for which aft appendage forces are significant, this influence should be reduced to an acceptable value.

The simplest model, using a single potential source to represent the blockage, was used by Allen [12] to derive the velocity perturbation, $\Delta u'$, at a distance x ahead of a source representing a sting flare, or support, with diameter D_S:

$$\Delta u' = -\left(\frac{D_S}{4x}\right)^2$$

This model is sketched in Figure 10a for a typical sting and flare arrangement. It is assumed that the sting diameter is small. The potential source is located so that the flare approximates the induced dividing streamline [28]; a reasonable choice is midway between the beginning and

end of the flare so that the flare (neglecting sting diameter) and support are matched both at the source and far downstream. If the distance x is $5D_S$, then $\Delta u' = -0.25\%$, or (since the velocity perturbation is small) $\Delta C_p = 0.5\%$. Allen comments, using his formula as a criterion: "... although experimental information is meager, a somewhat greater length should probably be employed" to account for additional viscous effects [12].

Tunnell [29] proposed a more elaborate model which is frequently quoted in the literature. He applied axisymmetric potential flow theory to a parallel sting with a downstream flare, taking account of sting diameter. With the additional parameters sting length, ℓ_s (which, measured from the start of the flare, is negative), sting diameter, d_s, and flare length, L_S, he derived the pressure perturbation at the model end of the sting:

$$\begin{aligned}\Delta C_p \;=\; & \left(\frac{D_S - d_s}{2L_S}\right)\left[\frac{1}{\sqrt{\left(\frac{2\ell_s}{d_s}\right)^2+1}} - \frac{\left(\frac{D_S}{d_s}\right)}{\sqrt{4\left(\frac{L_S-\ell_s}{d_s}\right)^2+1}}\right] \\ & + \left(\frac{D_S - d_s}{2L_S}\right)^2\left[\sinh^{-1}\left(\frac{2(L_S-\ell_s)}{d_s}\right) - \sinh^{-1}\left(\frac{-2\ell_s}{d_s}\right)\right]\end{aligned}$$

The parameters of Tunnell's model are sketched in Figure 10b. Note that the flare half-angle θ is given by $\tan\theta = (D_S - d_s)/(2L_S)$. Equivalent predictions from the previous method are obtained by setting $x = \ell_s - 0.5L_S$. Tunnell's method is also valid only for small perturbations, so that $\Delta u' = -0.5\Delta C_p$, but it takes account of the sting diameter.

Sykes [30] offers a simplified version of Tunnell's model, but, given the simplicity of the original, there does not seem much point in using it. Indeed, Allen's model will often suffice; close agreement between Tunnell and Allen is illustrated in Figure 11 for $d_s = 1$, $L_S = 4$, and $D_S = 2$ and 4.

The longitudinal pressure gradient arising from support blockage is a significant factor in measuring drag, and corrections for sting supports can be significant. Clark and Rosenstein compared drag corrections for a sting and two alternative strut supports in model tests of the Osprey tilt-rotor aircraft [31]. A simple tail sting required the smallest corrections, but this result cannot be generalized.

Almost all sting designs incorporate a parallel, or almost parallel, length for several diameters aft of the model, and thereby minimize blockage problems. A number of exceptions were noted in the Introduction, but a notable one is the new sting for the CDNSWC rotating arm [21]; it has a substantially flared section where it enters the model. Tunnell's method predicts a velocity perturbation on the axis of between one percent at the aft appendage leading edges to well over ten percent at their trailing edges, see Figure 12 (the general arrangement is shown in Figure 3).

2.2.2 General Overall Effects

Savitsky and Prowse [32] concluded that a tail-sting influenced measurements of longitudinal added mass and drag on a missile model tested in the Stevens Institute No. 3 towing tank. However, because of uncertainties in both measurements — uncertainties attributed to the

Reynolds Number range (around 3 million) of the experiment — they were unable to quantify the interference. It was recommended that further experiments be done with side struts.

Cyran [33] attempted to define critical sting lengths and diameters based on the degree of interference found in measurements of a number of static and dynamic coefficients using a generic modern jet fighter design. The dynamic tests were conventional small-amplitude forced oscillations, ie: the sting itself was stationary, and therefore static interference effects could be presumed to dominate. Pitch, pitch slope and damping, and yaw slope were unaffected for $\ell_s/D_B \geq 2$, where D_B is body (base) diameter, as was yaw damping at Mach numbers below 0.6. Sting diameter in the range 0.4 to $0.73D_B$ had no significant effect. On the other hand, base pressure (and hence drag) was affected for $\ell_s/D_B \leq 4$, and diameter effects were significant; these are local interference effects, discussed further below. Cyran's conclusion that the moment coefficients were relatively insensitive to sting geometry is of interest because the influence of a sting on the moment has been observed for a number of different model configurations [34,35]. This insensitivity may be specific to models for which the base diameter D_B is significantly greater than sting diameter d_s.

2.3 Local Sting Interference

Local interference is closely related to downstream blockage, but whereas we discussed blockage in terms of the downstream structures, here we emphasize the afterbody and base characteristics. The connection between these two aspects of sting interference is brought out by Gloss and Sewall [36].

The most commonly-cited example of local sting interference is the effect of a tail-sting on base pressure and, consequently, drag. This has been a constant concern in the transonic and supersonic testing of projectiles and jet aircraft (which is invariably done using a sting to minimize shock interference) and remains so today [37]. Drag is also affected by delayed afterbody separation in the presence of a sting; this effect is well-documented for spheres in subsonic flow (see Chapter VIII of Hoerner [38]), for example.

For projectiles and jet aircraft, base drag is often a significant fraction of the total. Experimenters have rationalized using a tail sting support by arguing that the sting occupies a space that would otherwise contain the wake or jet [12]. Nevertheless, obtaining accurate values for the base pressure or drag is difficult, and many systematic studies have been done to obtain corrections [4,30,37,39]. The common elements are that the body (fuselage) is terminated by a simply-truncated (cylindrical) or boat-tailed base, and that the sting diameter is often a substantial fraction of the base diameter — in the case of Kurn's study [39], between 50 and 100 percent, for example.

Lee and Summers [4] measured base pressure, total drag, and afterbody drag distributions on projectiles in axial flow, using tail-sting and alternative supports. They found that, in subsonic flow, a boat-tailed configuration was much more susceptible to sting interference than a cylindrical one, presumably because of afterbody separation. Sting length effects were negligible for $\ell_s/D_B \geq 6$ to 6.5, where D_B is the base diameter, but base drag was influenced by all sting diameters. Sykes [30] tested cylindrical and boat-tailed afterbodies with projectile driving bands and effectively infinite forebodies, in axial flow. He found good agreement between the

two afterbody geometries for the length effect and derived an empirical relationship between the base pressure correction, flare angle, and the ratio ℓ_s/D_B (Figure 13). His other results essentially confirmed those of Lee and Summers although he cautions: "data from other afterbody geometries should not be used in detail for the correction of pressure distributions or drag of conical boat-tailed afterbodies for sting diameter effect".

Uselton and Haberman [40] reviewed sting interference research conducted at the Arnold Engineering Development Center (AEDC), including that of Cyran [33], and some work with a modified version of the missile configuration studied by Savitsky and Prowse [32]. They did not distinguish between downstream blockage and local interference, but their findings regarding sting geometry are generally consistent with those of other investigators. However, their conclusion that: "with proper selection of sting hardware, ... tests can be conducted with negligible sting interference effects ..." must be regarded as over-optimistic, especially in overlooking constraints such as requirements for stiffness and strength.

Of the model geometries discussed above, most have limited application to the MDTF. Both Tunnell [29] and Gloss and Sewall [36] investigated sting interference on models having streamlined afterbodies with little exposed base area — a similar situation to submarine model testing. Tunnell relates the interference he observed primarily to blockage and concludes that local interference is negligible when sting diameter is almost equal to that of the base. An angle of attack up to 16.4 degrees had little effect on Tunnell's results. Gloss and Sewall measured base pressures and body pressure distributions in axial flow for Reynolds numbers up to nearly 75 million (based on body length). They noted that afterbody pressure distributions may be particularly sensitive to sting geometry when the blockage is high, and that a sensitivity to Reynolds number is observed in the same situation.

Viswanath and Rajendra [37] conducted systematic tests on models with streamlined afterbodies in axial flow in order to obtain base pressure and afterbody drag corrections for tapered stings. They concluded that, so long as flow on the afterbody was fully attached, there was no significant Reynolds number effect — in their experiments, Reynolds number was typically 8 to 9.5 million, and Mach number was 0.6 or higher. They introduced additional parameters, sting taper half-angle, θ_s, maximum body diameter, D_M, and afterbody angle at the base ("boat-tail angle"), β, see Figure 14. If sting and base diameters are approximately equal, correction to afterbody drag is [37]:

$$\Delta X'_{\text{aft}} = K_2 \left(\frac{d_s}{D_M} \right)^{1.35} + K_3 \theta_s$$

where K_2 and K_3 may be interpolated from:

β (deg.)	K_2	K_3
4	0.025	0.143
8	0.048	0.143
12	0.064	0.258
16	0.092	0.258

Applying the correction as presented above to submarine or submersible measurements on the MDTF clearly requires a great deal of caution, but it indicates that appropriate semi-empirical drag corrections may be possible with further experimental work.

Local sting interference also arises from the influence of the sting and support on asymmetric afterbodies and on asymmetrically-mounted aft lifting surfaces. Both these aspects of asymmetry are present in transport and cargo aircraft [5,35,41,42,43]. A number of investigators have also studied idealized slanted-base models [13,14]. Most submarine configurations are not significantly asymmetric in either respect, but the results of these studies may be useful in particular cases. In general, this effect is very difficult to uncouple from that of model modifications, discussed in the next section.

Asymmetric afterbodies lead to local vortex shedding even in axial flow [13,14], and a tail sting will clearly influence these vortices. The analogous situation for submarine models may be sting interaction with deck edge vortices and with the junction vortices generated at the root of the sail. In non-axial flow (for the static case at least) other vortices, such as those shed from the lee side of the afterbody [44], will be convected away from the sting.

Carter [41] demonstrated sting-induced pressure perturbations on the tailplane and afterbody of an aircraft model, resulting in discrepancies in pitching moment, tailplane effectiveness, and longitudinal stability. A significant portion of the tail cone was cut out to accommodate the sting. Local tailsection force and moment measurements were made to assess the local interference. He notes that interference was negligible more than one diameter forward for a parallel sting, and that it was insensitive to a modest range of incidence at low Mach numbers. Later he summarized the influence of a tail sting on the static force and moment coefficients for some transport aircraft configurations, and characterized the effects as significant but unavoidable [42].

Loving and Luoma [35] corroborated Carter's early work, finding corrections for lift and drag to be small, whereas that for pitching moment was quite significant. Taylor *et al* [5] determined a number of drag corrections, including that for sting interference using tailsection force and moment measurements. More recent observations by Carter and Pallister [43] resulted in substantial drag corrections for local interference which varied roughly linearly with incidence, Figure 15a. The effect of pressure in the sting tunnel (ie: the cavity through which the sting enters the model, see Figure 15b), which is equivalent to a base pressure, was judged to be significant.

Sidewash induced by circulation about the forward vertical strut is an effect specific to the MDTF. In Mackay and Walker [2], local drift angle and flow speed were estimated as functions of distance ahead of a streamlined strut. Figure 8 of that reference is reproduced here as Figure 16; the (quasi-static) drift angle of 30 degrees is excessive for normal dynamic testing, but might be achieved in a low Reynolds number experiment. Two strut chords ahead, the flow angle perturbation was about one degree, and the velocity perturbation just over one percent; both increased rapidly below about one chord ahead of the strut.

2.4 Interference Arising From Model Modifications

For axisymmetric afterbodies, sting mounting usually involves little more than simple truncation. This will result in modification of the drag and longitudinal moments because of the missing hull, a drag contribution from the static pressure in the sting tunnel, and possibly a base drag if the base diameter is much larger than that of the sting. In some cases, the afterbody

itself is modified to conform to (see Figure 4b) or shroud the sting and, if the sting diameter is large, aft appendages may be truncated or modified at the root. As previously noted, it is very difficult in practice to uncouple the effect of model modifications from local interference effects. In general both are simply included in total sting interference when deriving an experimental correction [26,45]. Accordingly, very few of the references reviewed here have addressed this issue.

The study of store separation by Dix [34] was concerned with preserving the stability characteristics of sting-mounted axisymmetric stores tested on the AEDC Captive Trajectory System [46]. It was observed that simple truncation had no effect in some cases, but influenced the longitudinal moments in others. In these, the presence of the sting could counteract the effect of truncation to some extent. Modification of aft appendages was also observed to affect longitudinal stability.

The missing hull effects for asymmetric afterbodies may not necessarily be large or strongly asymmetric as might be supposed [41]. Neither are model modifications: even the fairly bulky fuselage extension employed by Taylor *et al* [5], which also involved some changes at the tailplane root of their VC 10 model, did not apparently make a large contribution to the drag correction. Nevertheless, it is prudent to avoid modifications to lifting surfaces if possible. The criterion for the MDTF was that sting diameter not exceed 25 percent of hull diameter; a survey of modern designs showed that this should avoid modification of the aft planes or rudders. The feasibility study indicated that this restriction could be met [47].

In a number of aircraft and missile tests it is observed that the effects of model modification and local interference appear to diminish as transonic flow is approached. This has been reported by Simper and Hutton [48] in comparison with flight test data, and confirmed by Dix [34]. Such tests rarely go into the low subsonic region, so extrapolation down to incompressible flow is uncertain.

An additional difficulty particular to sting-supported submarine configurations is the modification that must be made to conventional propulsion arrangements, ie: a single propeller or ducted propulsor at the stern. Many tests will be satisfactory if the propulsor is simply omitted. Others, where the influence of the propulsor on the aft body and appendages is significant, require a mass-flow device capable of reproducing the propulsor-induced flow in this region [2]. This is shown schematically in Figure 17, and could consist of a porous suction disk or be a specially modified propeller. If the propulsor itself is to be modeled (eg: to obtain the influence of crossflow upon *it*), then tail sting support is not feasible; swords or some alternative support must be used and the compromises that result must be accepted.

3 Dynamic Sting Interference

3.1 Overview

We can distinguish between small-amplitude experiments in which the sting is stationary and the model oscillates (eg: Cyran [33]), and larger-amplitude experiments in which the sting itself is in motion. Hanff and O'Leary reviewed small-amplitude techniques in Reference [49], and

noted that much less effort had been devoted to understanding dynamic sting effects than to static effects. Nevertheless, it is reasonable to assume that static sting effects predominate in low-amplitude testing.

Hanff has also reviewed large-amplitude dynamic testing in wind tunnels [50]. In aerodynamics, these techniques are used to obtain nonlinear data, frequently in one degree of freedom only. Multiple degrees of freedom, cross-coupling effects, and time-history effects are often neglected because of experimental complexity.

Many of the references cited here use aerodynamic stability axes which distinguish between rotation of the vehicle and rotation of the incident flow vector (see Section 7.10 and following of Reference [51]). Experimentally, these are difficult to uncouple, and pitch damping derivatives, for example, are often reported as a lumped term: $Cm_q + Cm_{\dot{\alpha}}$.

A good review and extensive bibliography (to 1983) of support interference in unsteady aerodynamic testing was given by Ericsson in Reference [11]. Two interference mechanisms reviewed in this section are dynamic afterbody separation and downstream vortex bursting — the latter because, for the MDTF, it may be more significant as a dynamic than a static interference mechanism. We should also reiterate that many of the modes of static interference previously discussed, eg: sting/vortex interactions, may also appear intermittently, or as unsteady effects, in dynamic tests.

3.2 Dynamic Afterbody Separation

Wehrend [52] did low-amplitude (up to ±3.5 degrees) dynamic experiments with flat- and spherical-based cones (re-entry bodies) at angles of attack from -13 to 18 degrees. He measured pitch damping in addition to the usual static coefficients, and ran variations of sting length and diameter. His models are sketched in Figure 18 and the sting variations in Figure 19. At the lowest Mach number, 0.65, sting effects were negligible for the flat-based cones, but were significant for the spherical-based models. Both length and diameter effects were observed in the latter case, see Figure 20; only the longest sting with $\ell_s/d_s \approx 8$ eliminated them.

Wehrend did not offer an explanation for his results, but they most likely arise from the influence of the sting on afterbody separation. On flat-based models, separation would be fixed at the circumference of the base and not be subject to sting influence except possibly at extreme incidence for large sting diameters; neither condition occurred in this experiment. On the other hand, for spherical-based models, free (ie: non-fixed) separation on the base would be highly susceptible to sting interference as suggested by Ericsson and Reding in their analyses [53,54,55] of re-entry vehicle testing.

For dynamic afterbody separation to be relevant to submarine testing on the MDTF, two conditions must be met: first, that a sufficient degree of separation be present on the afterbody; and second, that the location of separation be sensitive to unsteady flow. Both depend on parameters such as afterbody geometry and Reynolds number. Mabey *et al* [10] cite free (ie: untripped) transition as an exacerbating factor for the occurrence of dynamic separation in general, and it is relevant that the irregularity and unpredictability of this form of interference prompted Viswanath and Rajendra to require attached flow on the afterbody as a prerequisite for applying their corrections [37]. Nevertheless, static testing suggests that there will be not

much tail separation at Reynolds numbers of a few million or more [24], and there is evidence that this form of local interference is insensitive to incidence unless downstream blockage is high [29,36]. Therefore it is likely that this effect will not be significant except, perhaps, on very full afterbodies, or for low Reynolds numbers.

3.3 Downstream Vortex Bursting

In 1980 Johnson *et al* [56] reported the sensitivity of static lateral stability to the interaction ("breakdown" or "bursting") of trailing vortices with downstream model support structures. The tests were conducted on arrow- and delta-winged bodies at incidences up to 40 degrees and sideslip up to 12 degrees. Vortex breakdown is characterized by a sudden expansion of the vortex from the classic highly localized vortex core to one of a number of a much larger swirling flow structures [57]. It occurs naturally, resulting from near-stagnation condition in the vortex core, and may be triggered by the presence of a downstream object. In Johnson's tests, premature breakdown of one or both of the leading-edge vortices was triggered by the sting support structure at a particular incidence, and spread rapidly forward with increasing incidence. The experimental results were sensitive to this because (i) for these models, the aerodynamic characteristics were dominated by the leading edge vortices; and (ii) the test set-up permitted asymmetric interaction with the downstream structure. Johnson cautioned: "... on model configurations having strong vortex lift characteristics, extreme care should be exercised in wind tunnel tests to avoid downstream obstacles which might artificially induce an adverse pressure gradient and result in premature vortex bursting".

Ericsson and Reding [53] cited this interference mechanism as prejudicing the use of a sting, or any support system with downstream elements, for high incidence aerodynamic testing. They subsequently extended this caveat to dynamic testing, pointing out the use of relatively massive sting supports [11] and the unsteady trajectories of trailing vortices [58]. Configurations employing vortex lift (ie: delta or highly-swept wings) were initially identified as particularly sensitive to this form of interference. Later reviews added the asymmetric vortices shed from a slender nose at high angle of incidence [6,9,59,60,61]. Unfortunately, there is much repetition in this series of references — in the present context, Reference [59] is distinguished largely by its alliterative title — but they illustrate the evolution in thought on this subject.

The essential elements for interference caused by vortex bursting appear to be:

- a model for which the aerodynamic characteristics are strongly determined by the trailing vortices;
- flow conditions for which natural vortex bursting is likely; and
- the presence of downstream obstructions.

The phenomenon has not been observed, to the author's knowledge, in static tests with submarine-like configurations. Perhaps the conditions outlined above are rarely present simultaneously; in general, except for the presence of a downstream obstruction, this is not easy to determine.

The principal trailing vortices from a submarine at an angle of drift are the sail tip vortex and the lower hull separation vortex [16,17,22,44]. In steady conditions, the sail tip vortex tends to follow the freestream streamlines while the weaker hull separation vortex is convected somewhat

closer to, but still diverging from, the hull in the classic manner of crossflow separation. Their influence may be significant; both affect the out-of-plane hydrodynamic coefficients to some degree by means of their contribution to crossflow aft of the sail, but the hull separation vortex is the more influential because it modifies circulation about the afterbody [44]. The hull separation vortex exerts a degree of vortex lift resulting in a sideforce and yawing moment, and interacts strongly with the aft appendages. In dynamic tests, either vortex may track close to the hull or tail during extreme manoeuvers, resulting in transient interaction forces. Therefore it is prudent to assume that the results of static or dynamic experiments with a submarine model may be sensitive to vortex interactions.

Incipient vortex bursting is difficult to predict, even for regular confined (eg: pipe) flows. Success has been reported in its numerical simulation, recently for delta-wing leading edge vortices [62], but the computational effort is quite intensive. Spall *et al* [63] have proposed criteria for its occurrence based on the Rossby number, $W/r^*\Omega$, where W is the axial velocity in the vortex at radius r^* where swirl velocity is a maximum, and Ω is the rotation rate of the vortex core in an equivalent Rankine model. They suggest that for wing tip vortices, breakdown occurs for Rossby numbers below about 0.65 at Reynolds numbers (based on r^* and W) above 100. For lower Reynolds numbers, the critical Rossby number is lowered, see Figure 21. Because the Rossby number is itself very difficult to measure or predict, the likelihood of incipient vortex bursting in MDTF experiments cannot be predicted, with confidence, in advance.

Estimating trailing vortex trajectories is reasonably straightforward; however, it may not be possible to avoid their interaction with the MDTF struts and beam for specific model trajectories, or because of other constraints; see Section 5.1. This form of interference may therefore require further attention if anomalous experimental results are observed.

4 Sting Interference Corrections

Ericsson recommended [6] the ideal approach to alleviating support interference to be: (1) identify the flow mechanisms through which the support interference acts; (2) design the support such that interference effects are minimized; and (3), if possible, derive the means by which corrections can be made. In practice, the experimenter is generally presented with an existing support arrangement and therefore proceeds directly to the third step, deriving corrections. Support interference corrections have traditionally been empirical, and are frequently time-consuming. Advances in the numerical prediction of complex flows promise a more efficient solution to the problem. Both approaches are outlined in this section.

4.1 Empirical Corrections

Empirical corrections are obtained with the classic image or multiple support method [26,45,64]. This requires repeating measurements with combinations of alternative support arrangements and is predicated upon the model and support flows being weakly interacting [14]; that is, that the support-induced flows (for each support arrangement used) are small perturbations of the overall flowfield. Despite the fact that this is infrequently the case (eg: [26]), and that there may be significant second-order effects unaccounted for, the multiple support method is

usually considered quite adequate for static testing. However, Dietz and Altstatt [64] judged that the image method was not satisfactory in tests of missile body at high angle of attack for which there were significant interactions between the alternative support arrangements. In general, the chief drawback of this technique is that test facility occupancy time may be greatly increased.

This procedure is not appropriate for the MDTF because of the difficulty of implementing the combined support arrangements, increased test time, and additional complexity of support interactions arising from time history effects. Nevertheless, it will be important to assess the degree of interference present by some comparative testing (both static and dynamic) of a standard submarine model with whatever alternative support arrangements are available.

4.2 Analytical and Numerical Corrections

Early non-experimental efforts at interference correction ranged from purely analytical [12,29] to semi-empirical methods [64], and could be considered reasonably useful for conventional static testing, although the analytical methods were based on much-simplified mathematical models. The current trend is to use numerical methods for predicting interference on more complex configurations, but this is still essentially restricted to static tests.

The most common numerical tools for predicting interference are panel codes. They are reasonably efficient and well suited to calculating the influence of blockage and model modification. Viscous effects may be predicted by coupling with boundary layer calculations provided that separation is not a dominant feature of the flow. Boeing has used the VSAERO panel code to calculate downstream blockage of support arrangements [65], and incremental drag attributed to the longitudinal pressure gradient was quite well predicted [31].

Unsteady panel codes will be particularly appropriate for evaluating experimental results from the MDTF. Canadair has modeled a submarine configuration using USAERO (Unsteady VSAERO). A preliminary time-stepping version of the CANAERO code (CANAERO-T) has been implemented [66] and further development is underway. CANAERO was developed especially for submarine modeling. These codes will have the capability to predict unsteady blockage and downstream vortex interactions with the MDTF sting, beam, and struts modeled.

Britcher *et al* observed that the reliability of many correction methods, including panel codes, which are linear in a number of respects, rests on the model and support flows being weakly interacting [14]. The same caveat was noted above for the multiple support empirical correction technique. Since the latter is often satisfactory despite this condition not being fully met, it is reasonable to assume that panel codes can be used with some confidence for obtaining interference corrections.

Yet more powerful tools are becoming available. Stanniland [67] described ARA experience with both panel and Euler codes. Baysal *et al* [68] used a three-dimensional finite-volume Navier-Stokes solver (VISCC) to study missile ejection from a weapons bay; the geometry modeled included a L-shaped sting support to provide complete simulation of verification experiments. This study included viscous, compressibility, and transonic effects.

5 Additional Sting-related Issues for the MDTF

5.1 Model Attitude

Model attitude (eg: testing upright, sideways, or inverted) influences interactions between the wake or vortices trailing from the model with the sting, beam, or struts. A turbulent wake impinging on downstream structures can excite vibration. The potential for premature bursting of the trailing vortices on downstream structures was reviewed in Section 3.3.

The attitude of the model is easy to select with a tail sting. In shallow submergence experiments, where the influence of the free surface is a factor, there is no choice but to test the model upright as shown in Figure 1. For deep submergence experiments, the probability of undesirable interactions may be reduced if the model attitude is selected as follows:

Predominant Mode	Model Attitude
Axial Flow	Inverted
Static Pitch, nose up	Inverted or Sideways
Static Pitch, nose down	Upright or Sideways
Static Yaw	Upright or Inverted
Dynamic Pitch	Sideways
Dynamic Yaw	Inverted

This table assumes manoeuvering modes relative to the MDTF geometry; that is, pitch in the vertical plane and so on. It would be modified if, for example, dynamic tests were done in a diagonal plane to maximize amplitudes. Note also that the choice of attitude is less clear in dynamic experiments in general and particularly for experiments in which no single mode of manoeuver is predominant.

Without a 360 degree roll capability, the complications from changing model attitude over the course of a test program, especially if change requires balance and transducer recalibration, would make the choice of a single, compromise, model attitude inevitable. Practical experience with the MDTF may result in guidelines other than suggested above.

5.2 Sting Deflections and Vibration

Sting deflections and vibration, because they are related to stiffness of the sting and its support structure, must be traded off against flow interference in designing a support arrangement or in selecting the size of model to be used with an existing support. An extreme example is that of Reed [17] who nearly doubled the diameter of the sting previously used by Kaplan [16] to avoid vibration; the new sting was 46 percent of hull diameter.

Model deflections under load can be accounted for in the data reduction provided that they are measured or adequately estimated [69]. Vibration, on the other hand, presents a more difficult problem. At worst, it will overload the balance. At best, it determines uncertainty limits on the measurements. Vibration may be reduced by limiting the excitation, by providing additional damping to the model, or by increasing support stiffness and hence natural frequencies.

Vibration has been noted as a problem in tests of slender axisymmetric bodies at high incidence [70]. Small asymmetric forces (which, for example, influence missile trajectories) may be masked by the sting vibration, or buffeting, excited by periodic vortex shedding. Ericsson [11,60] proposed criteria for coning experiments to overcome the problem. Ericsson's methodology is of interest (although it was derived for quasi-static testing) because there is a parallel in the measurement of out-of-plane forces on a submarine manoeuvering in the horizontal plane. These are typically small relative to the in-plane forces and consequently also susceptible to measurement error at low levels of vibration. Vortex shedding can occur from either the hull or the appendages at low model scale Reynolds numbers [71]. In DREA's experiments in the 2×3 metre wind tunnel, buffeting limited the drift angle to 20 degrees at the normal test speed [24].

Burt and Uselton [72] present analytical corrections for the effects of sting deflection and vibration on longitudinal stability derivatives obtained by forced-oscillation experiments. Limited validation is shown for small-amplitude experiments in which the corrections were relatively large. Beyers [73] compared this with some other published methods and suggested a simplified technique which determines and accounts for the effective shift in the center of oscillation of the model. However, these techniques are still restricted to low amplitudes of oscillation. Beyers' criterion that the first natural frequency be three times the frequency of oscillation is less stringent than that proposed for the MDTF (five times), noted below.

A tuned mass damper (TMD) is effective for reducing model vibration in static measurements, as demonstrated on DREA's Static Test Rig [25]. Tristrant and Beyers [74] cite the use of a TMD on a rotary rig using a TMD, referring to it as the 'pendulated mass technique', and Mabey *et al* [10] also discuss tuned dampers. In dynamic testing, this technique poses a number of serious difficulties, both logistical and related to excluding its frequency dependence from the measured data. For the MDTF, direct application of damping material to the sting [10] may be a simpler solution if additional damping is required.

Even with good damping, it is important that the model support have high stiffness and high natural frequencies. The MDTF feasibility study [47] proposed a lowest (or first) natural frequency of 5 Hz. This is equal to five times the highest operating frequency (1 Hz with a 2 metre model), and limits the dynamic error due to vibrations to no more than 4 percent in the worst case. With larger models, and lower operating frequencies, the dynamic error is further reduced.

Static frame tests of the pilot model MDTF showed excessive sting deflection and a first natural frequency of about 2.8 Hz [3,75]. A finite element analysis of the sting, described in Appendix A, suggests that the sting is adequately designed, but that its attachment to the beam joining the struts may be insufficiently rigid. With proper attention to this in the production MDTF, additional damping should be unnecessary.

It should also be noted that the vertical struts on the pilot model MDTF are unfaired. This may result in additional vibration from vortex shedding on the struts when the pilot MDTF is tested on the towing tank carriage. The problem is unlikely to arise with the production MDTF because fairing the vertical struts is required for drag reduction. This reduction in drag is necessary in order to meet the Reynolds number requirement of 15×10^6 for models between two and six metres long; see Figure 22.

5.3 Exotic Materials

The RAE Acceleration Rig has some innovative features including a carbon fibre sting [76]. Griffin *et al* [77] proposed an 'ideal' composite sting design for the US National Transonic Facility. These are exceptions; almost all model support systems are made from conventional materials, typically steels. Canadair considered exotic materials in the MDTF feasibility study [47] and concluded that, except for weight, the alternatives did not offer any practical advantage. In the MDTF, the sting is only a small part of the total system weight in motion, so even this advantage is diminished. Figure 23, reproduced from Reference [47], shows sting natural frequency as a function of diameter for a number of different materials.

5.4 Closed Loop Control

Mackay and Walker introduced the possibility that the MDTF could be operated under closed loop control, or 'trailing mode' [2]. In this mode, forces on the model are fed back to the control system so that free model trajectories can effectively be reproduced. This technique is discussed in two of the reports reviewed for this study (References [78] and [79]); in both cases it was used to simulate stores separation with captive models, and sting supports were employed to sufficiently reduce interference. For submarine testing, some form of propulsion modeling is necessary with this technique, and the conflict with a tail sting was discussed in Section 2.4. It may well be that a simple representation of thrust and torque is sufficient; if so, calculated thrust and torque components can be input directly into the control system algorithms without incorporating a propulsor.

6 Conclusions

The MDTF has a number of unique features relating to support interference that will take some time and experimental effort to fully understand. While not all the literature reviewed here is directly applicable to the MDTF, there is sufficient information presented to anticipate some of the potential problems associated with testing submarine models on a tail sting.

Overall static interference is determined by the dimensions of the sting and its supporting structure. Methods for its prediction, ranging from very simple analytical models to quite complex panel codes, appear to be adequate for an assessment at the design stage. The MDTF configuration provides a relatively low level of downstream blockage interference, and this should be true for the production model supporting a 4 to 6 metre model.

Some local interference, and effects due to model modification, will be unavoidable using a tail sting, although comparison between different methods of model support (eg: Figure 6) suggests that the effects fall within typical experimental uncertainty. Nevertheless, since levels of uncertainty are often unacceptably high, these effects merit further investigation. The empirically-based studies cited here provide useful guidelines but the degree of their applicability to the MDTF is not clear. It is certain that accurate measurement of drag on a sting will be difficult, and possible that basic resistance and propulsion experiments, when required, would be better carried out with an alternative support system.

Afterbody separation and downstream vortex bursting have both been reviewed in the context of dynamic tests. While there is little evidence that either is a significant factor in testing submarine-like configurations, the amount of relevant data is small. The likelihood of premature vortex bursting or other interactions may be reduced by choice of model attitude. Until sufficient experience has been gained with the MDTF, it will be prudent to consider these interference mechanisms in the case of apparently anomalous results.

It is feasible to design a sting for the production MDTF which can support submarine models up to 6 metres long with a sufficiently low level of vibration and a tolerable degree of interference. There is no significant advantage to using exotic materials or elaborate damping techniques. Some experimental and analytical studies will be required to determine the need for corrections to specific measurements, but this review suggests that, with due caution and attention to experimental procedures, results obtained using a well-designed tail sting support will have an acceptable level of experimental uncertainty.

7 Recommendations

The following recommendations are directed towards submarine testing on the production MDTF.

- The parallel, or near-parallel, part of the sting should be at least five diameters long from where it enters the model, and preferably longer — a length of about five downstream support diameters is cited to minimize blockage effects. Sting diameter where it enters the model should not exceed 25 percent of model diameter.
- Rigidity of the connection of the sting to the beam assembly should be rigorously checked to ensure sufficiently high natural frequencies.
- The struts should be streamlined according to the proposal in the feasibility study in order to reduce drag. The beam and beam/strut bearing arrangements should be faired and their dimensions minimized. These actions will also minimize the likelihood of vibrations induced by vortex shedding from the model support structure.
- Numerical evaluation of sting/model interactions should be made with whatever codes are available (eg: panel code analysis for blockage, boundary layer calculations for afterbody separation). Flow visualization, possibly in a wind tunnel, may be required for validation.
- MDTF experiments should be carried out for comparison with other data. The most obvious candidate for testing is the Canada/Netherlands standard model which has been extensively tested, in a number of variants, in the IAR wind tunnels, and in the MARIN towing tanks.
- Evaluation experiments should also be done with alternative support arrangements on the MDTF itself. In particular, the evaluation test model should allow for a twin-strut (PMM type) support arrangement in addition to the sting. These tests should include drag and longitudinal added mass in addition to other selected experiments.
- The possibility of modeling propulsion with the tail sting should be investigated further.

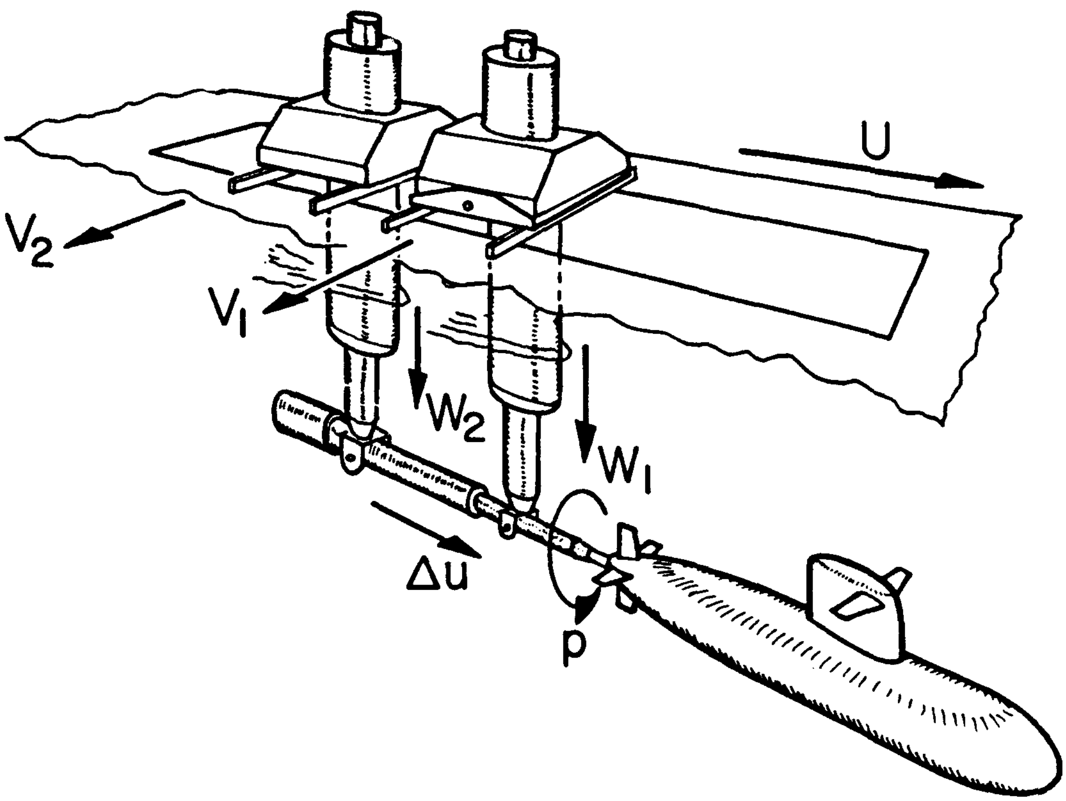
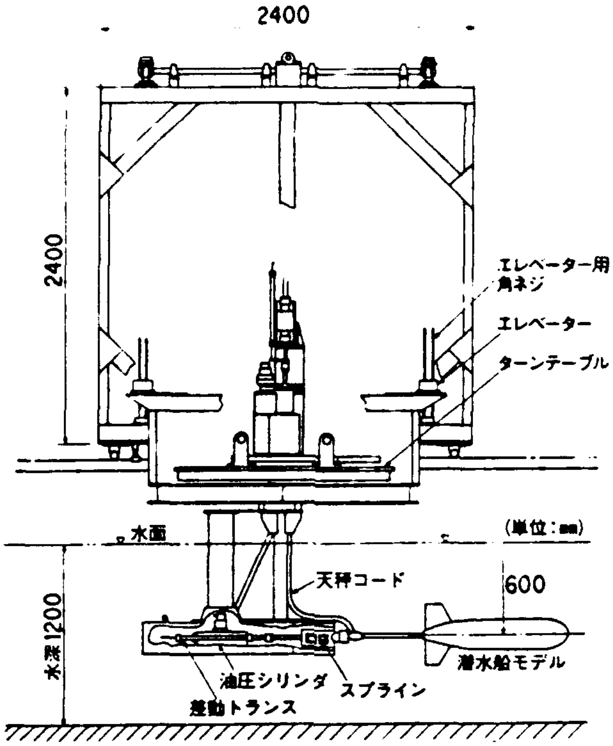
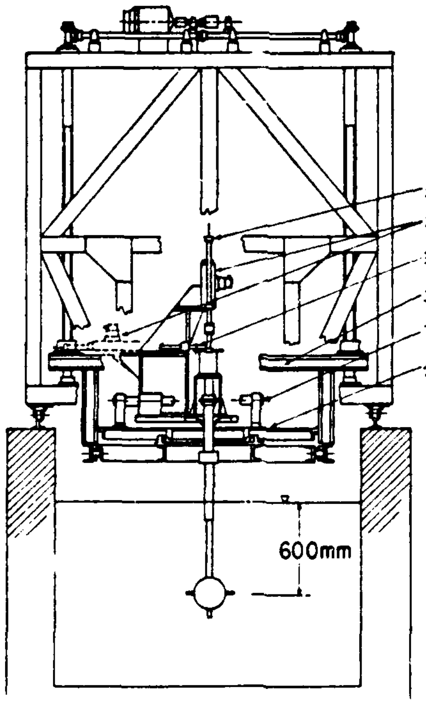


Figure 1 *MDTF General Arrangement for Submarine Testing*

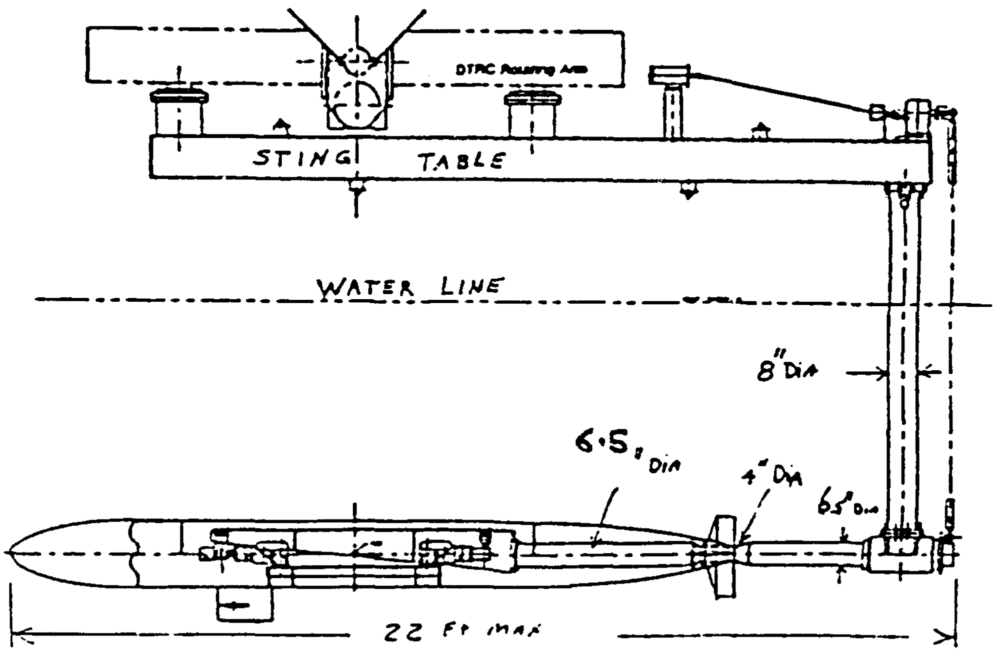


実験装置の構成図（その１：sting 法実験）



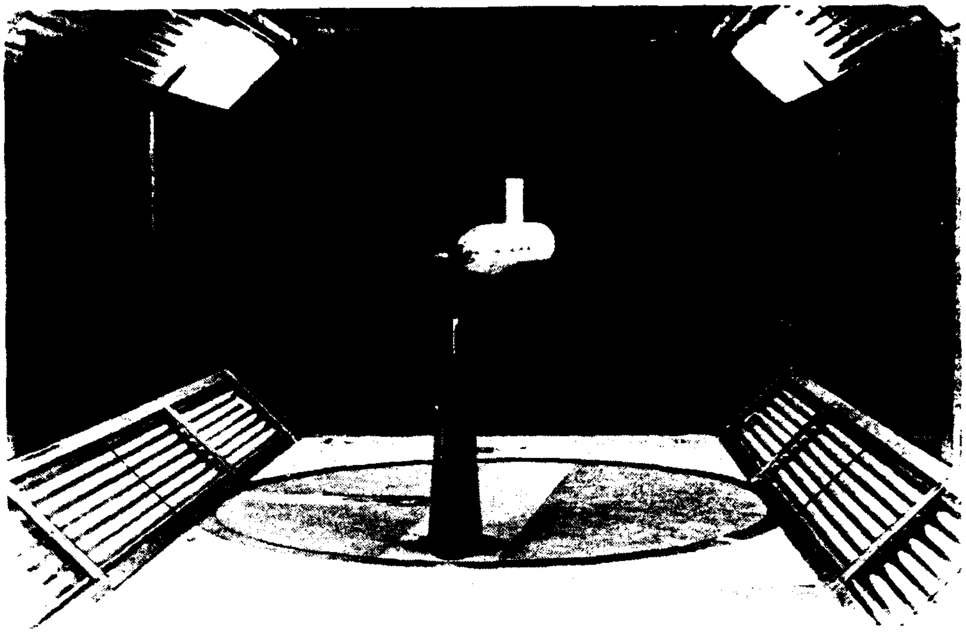
実験装置の構成図（その２：strut 法実験）

Figure 2 *Iitaka's Modified PMM (reproduced from Reference* [20]*)*

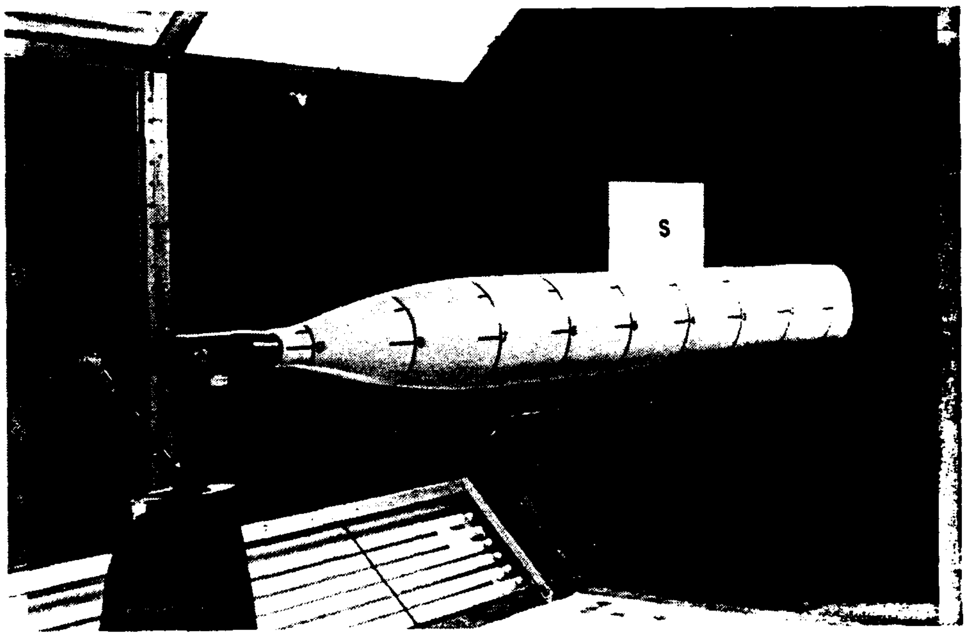


Model and Sting Support System from CARDEROCKDIV Rotating Arm Facility

Figure 3 *CDNSWC Rotating Arm Sting Arrangement (reproduced from Reference [21])*

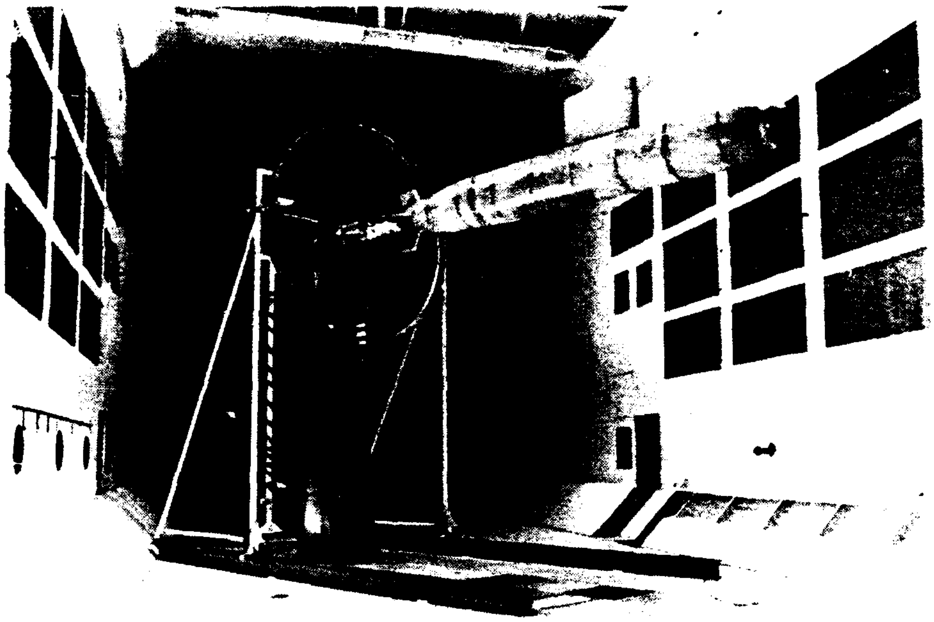


a) General Arrangement

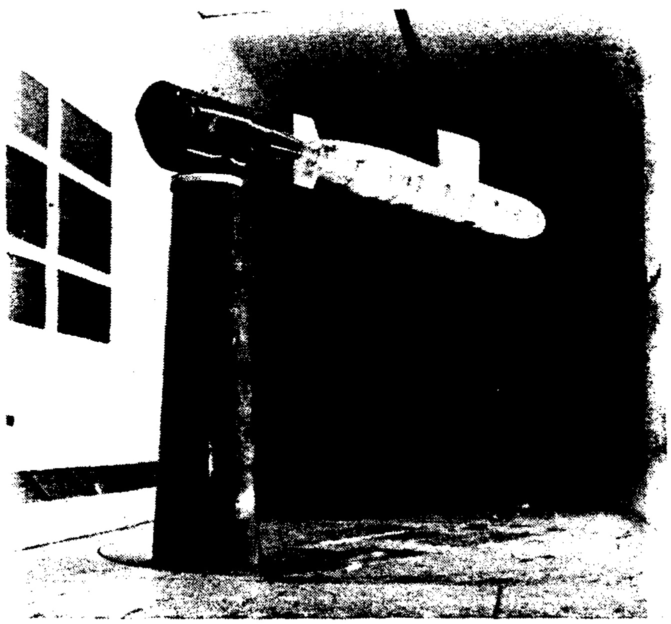


b) Sting Details

Figure 4 *Submarine Model Testing in the IAR 2 × 3 metre Wind Tunnel*

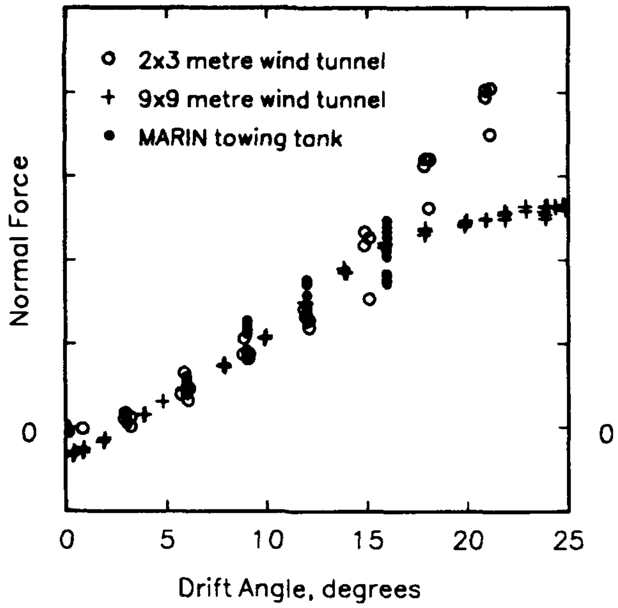


a) Original Sting Arrangement

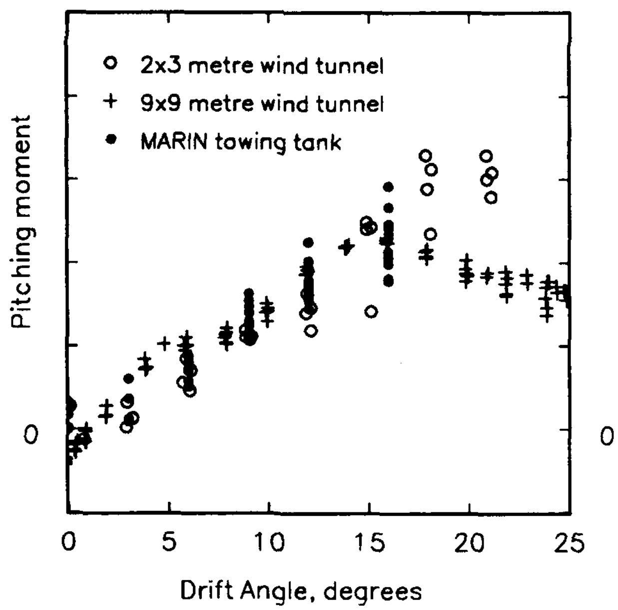


b) Modified Sting Arrangement

Figure 5 *Submarine Model Testing in the IAR* 9×9 *metre Wind Tunnel*



a) *Normal Force*



b) *Pitching Moment*

Figure 6 *Out-of-Plane Force and Moment on a Submarine Hull + Sail Configuration*

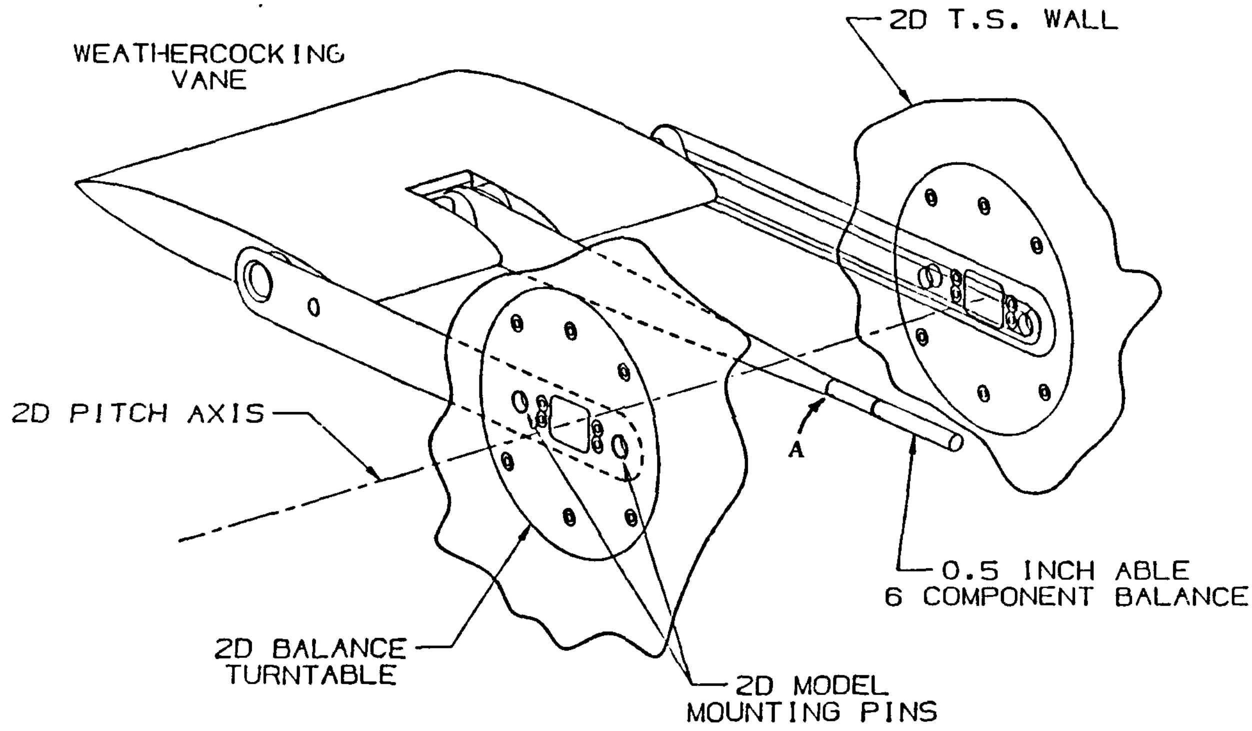


Figure 7 *IAR Blowdown Tunnel Sting Support (reproduced from Reference* [27]*)*

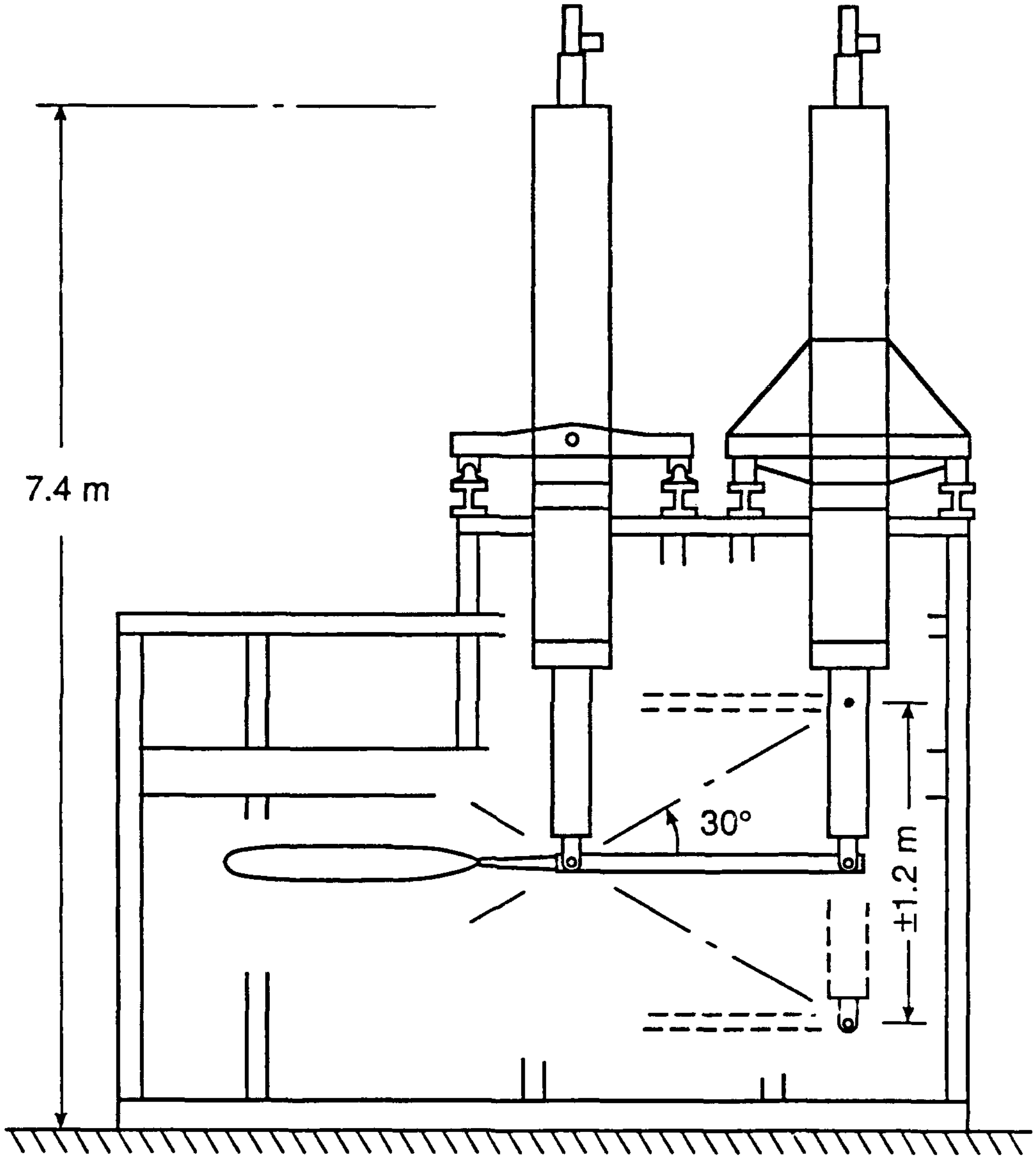


Figure 8 *MDTF Pilot Rig in the Static Test Frame at Canadair*

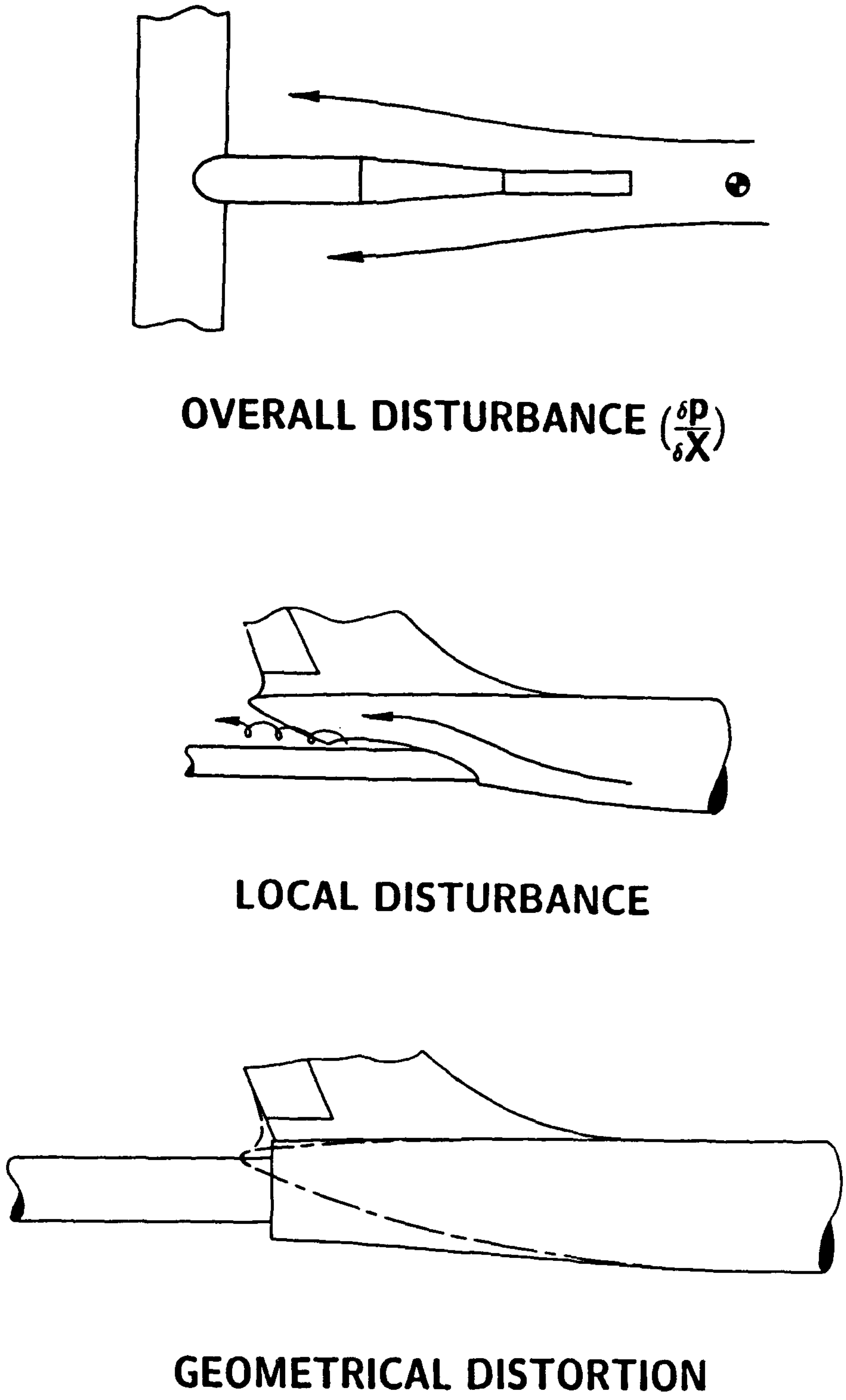
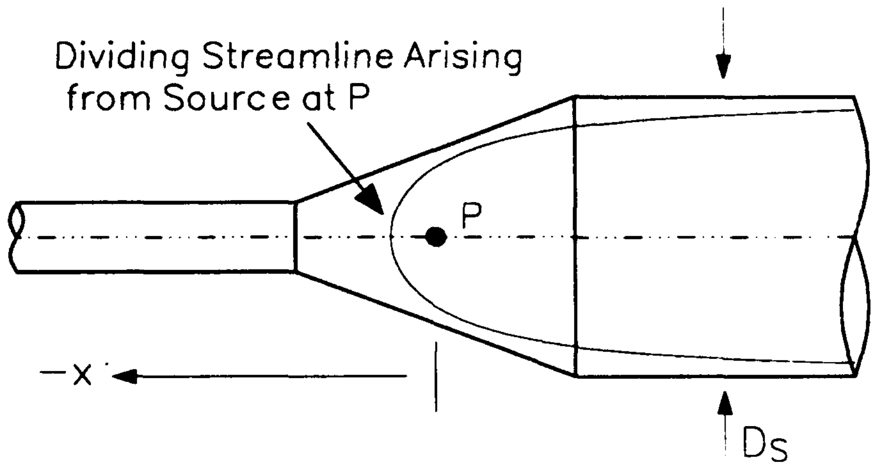
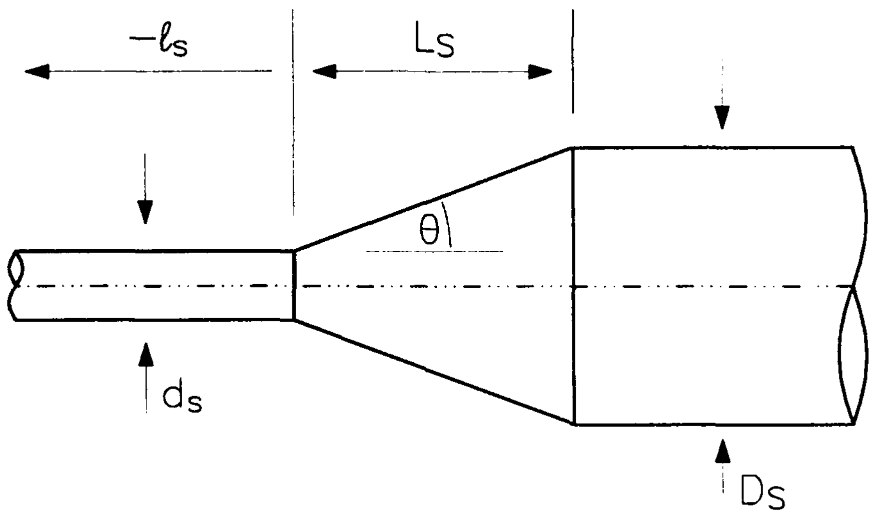


Figure 9 *Components of Static Sting Interference (reproduced from Reference [14])*



a) *Allen* [12]



b) *Tunnell* [29]

Figure 10 *Downstream Blockage Models*

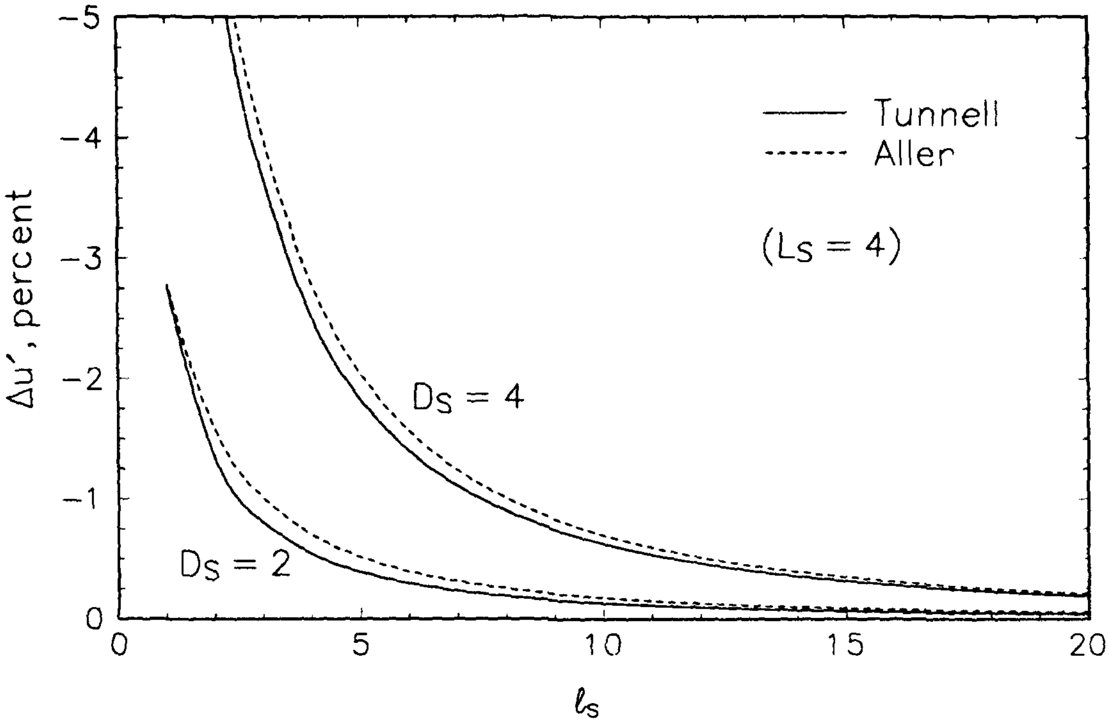


Figure 11 *A Comparison of Downstream Blockage Models for $d_s = 1$, $L_s = 4$, and $D_s = 2$ and 4*

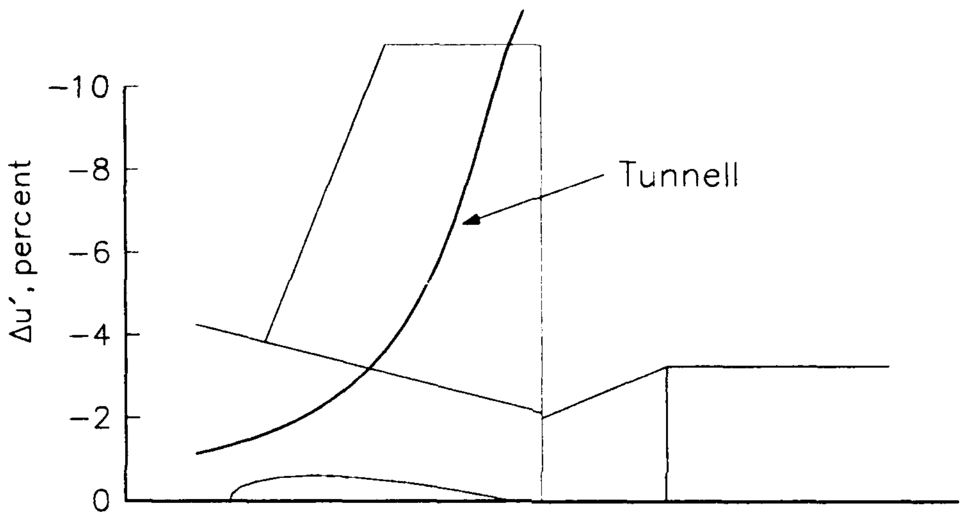


Figure 12 *Downstream Blockage on the CDNSWC Rotating Arm Sting*

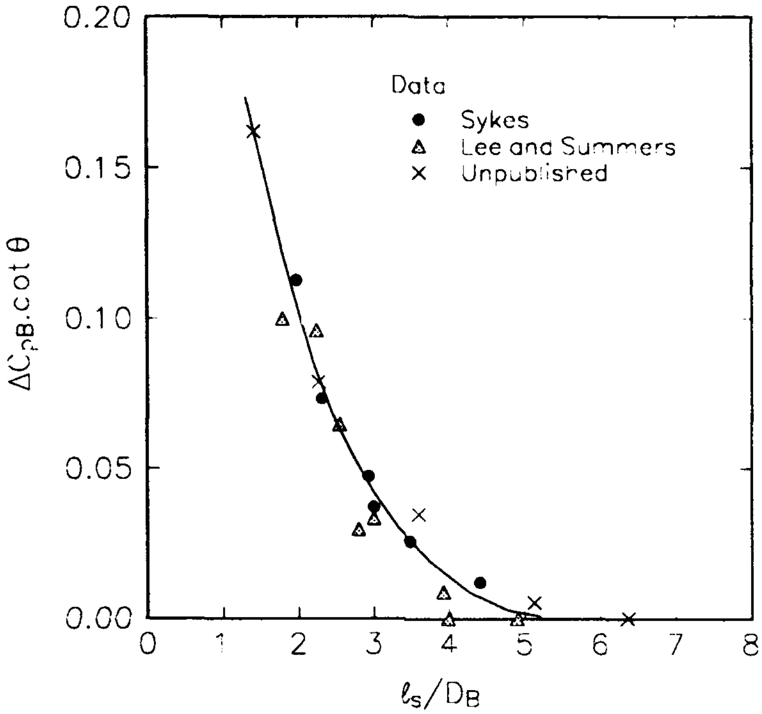


Figure 13 *Sykes' Base Pressure Correction (modified from* [30]*)*

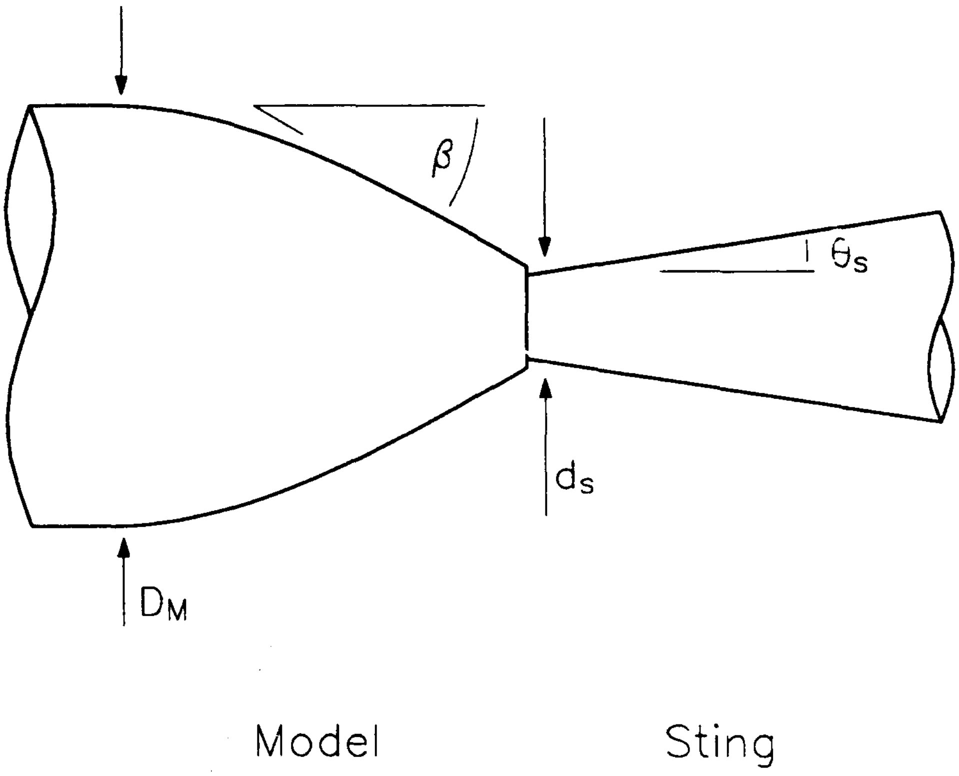
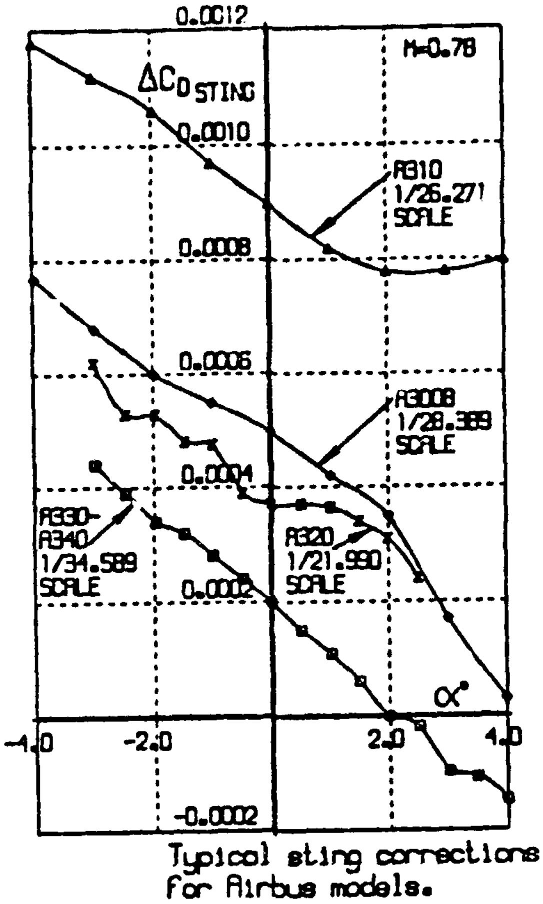
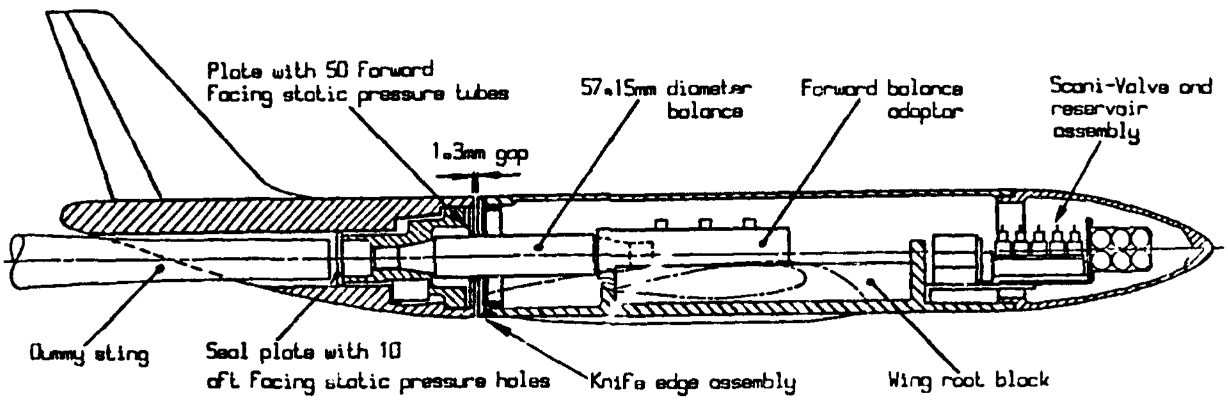


Figure 14 *Viswanath and Rajendra* [37] — *Notation*



a) *Drag Correction vs. Incidence*



b) *General Arrangement: the model was supported at each wing tip while the balance measured afterbody forces in the presence of the dummy sting*

Figure 15 *Local Sting Interference in Transport Aircraft Tests (reproduced from Reference [43])*

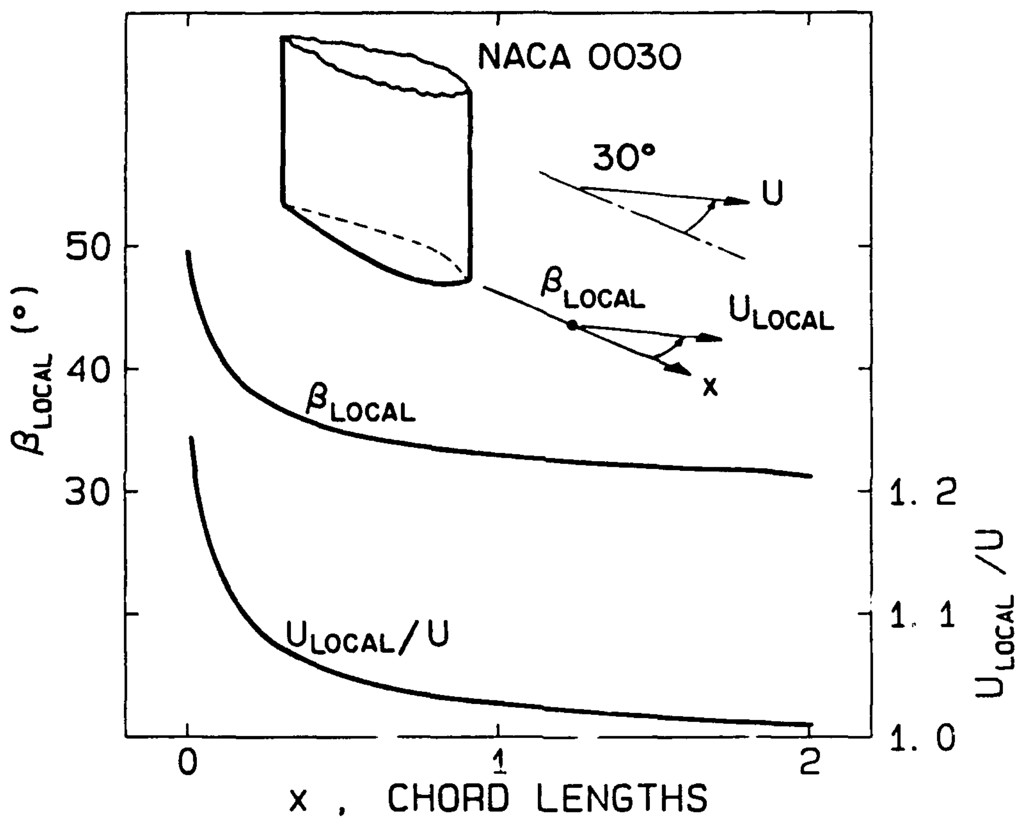


Figure 16 *Local Drift ..ngle, β_{LOCAL}, and Flow Speed, U_{LOCAL}/U, forward of a Semi-Infinite Strut moving at 30 degree Drift with veloci; U (reproduced from Reference [2])*

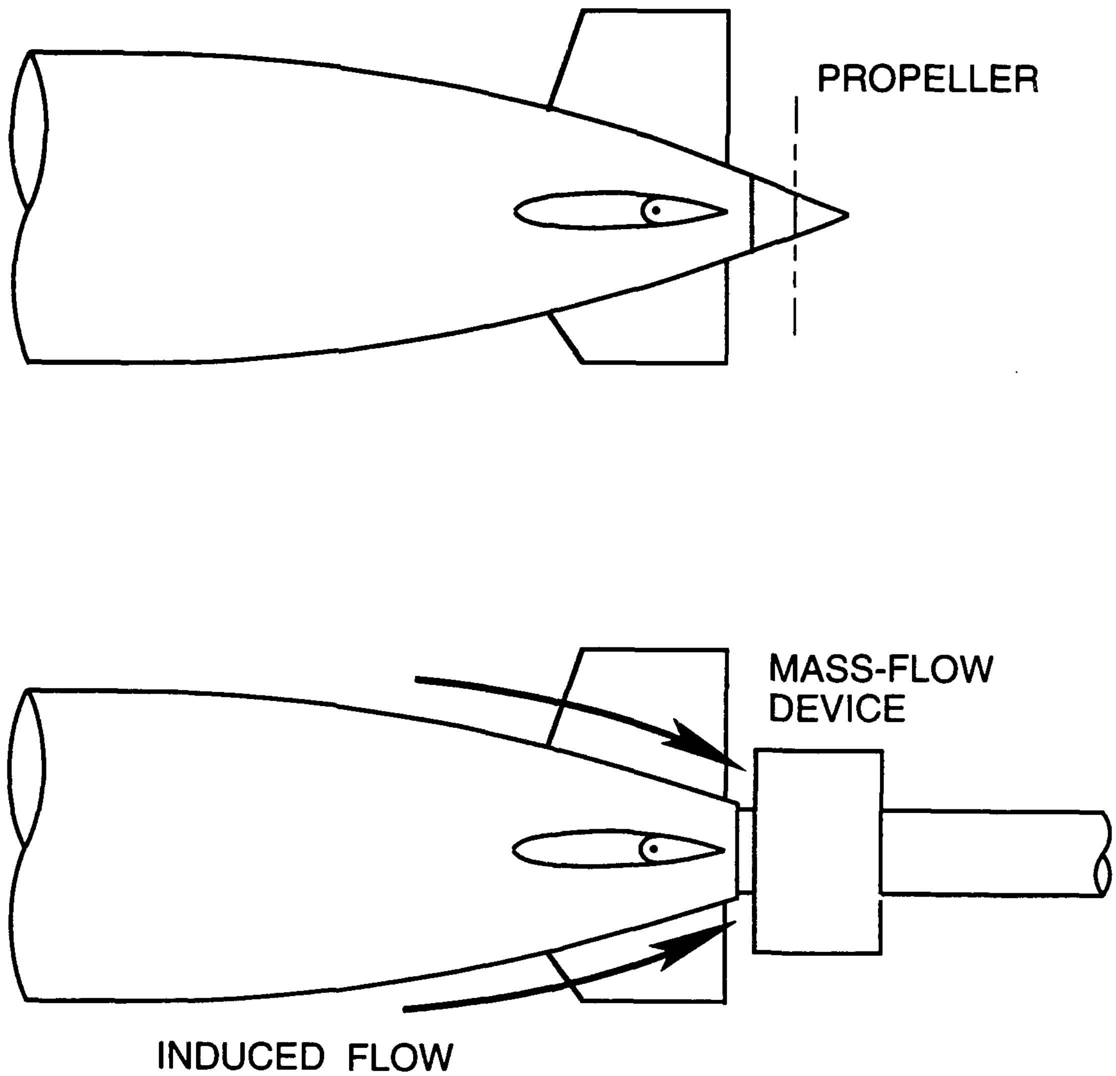


Figure 17 *Propulsor Modeling with a Tail-Sting Support*

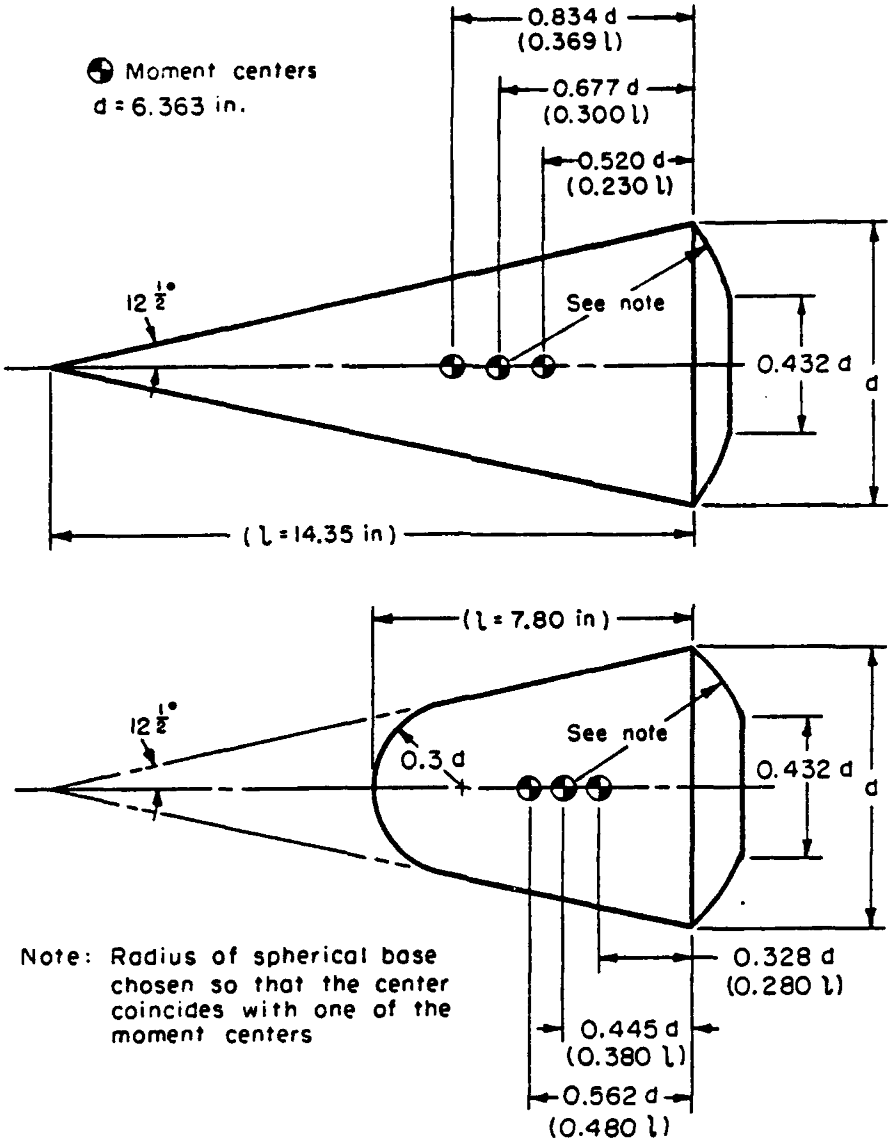


Figure 18 *Wehrend's Models (reproduced from Reference [52])*

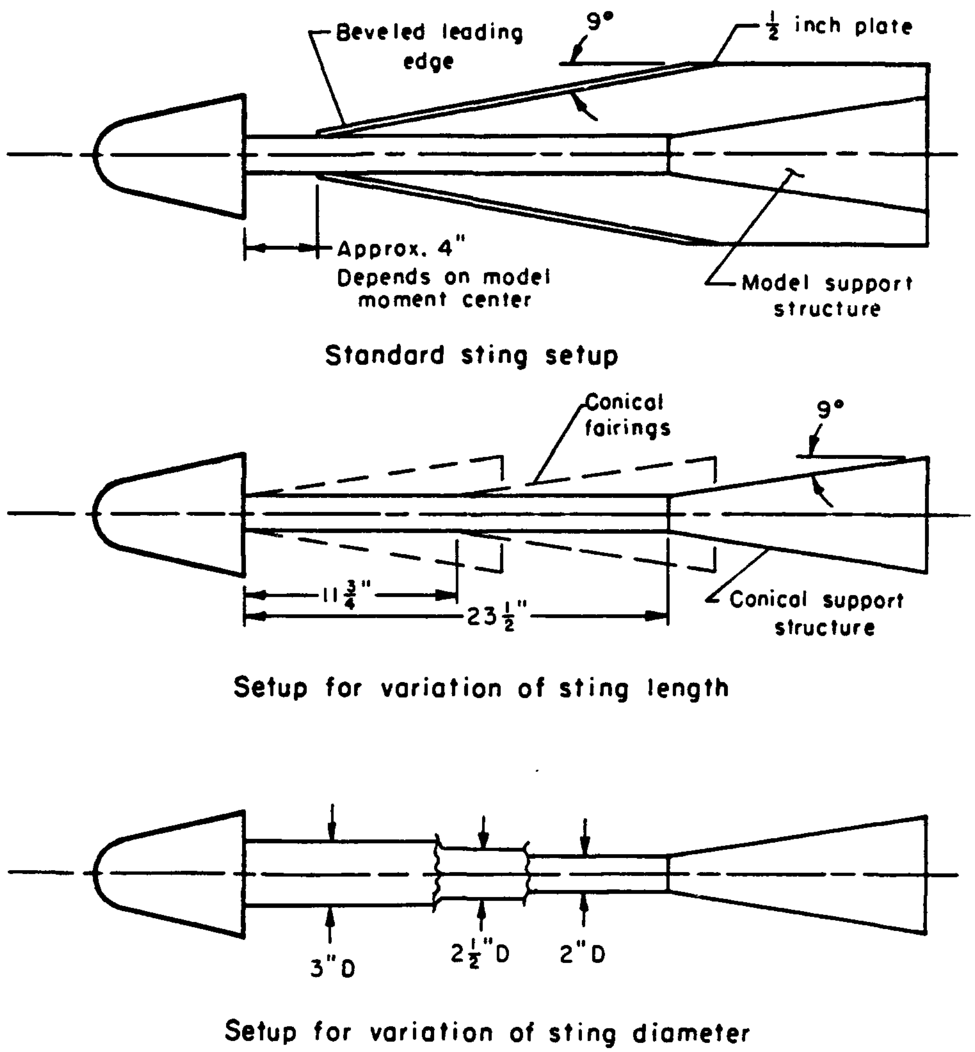


Figure 19 *Wehrend's Sting Variations (reproduced from Reference [52])*

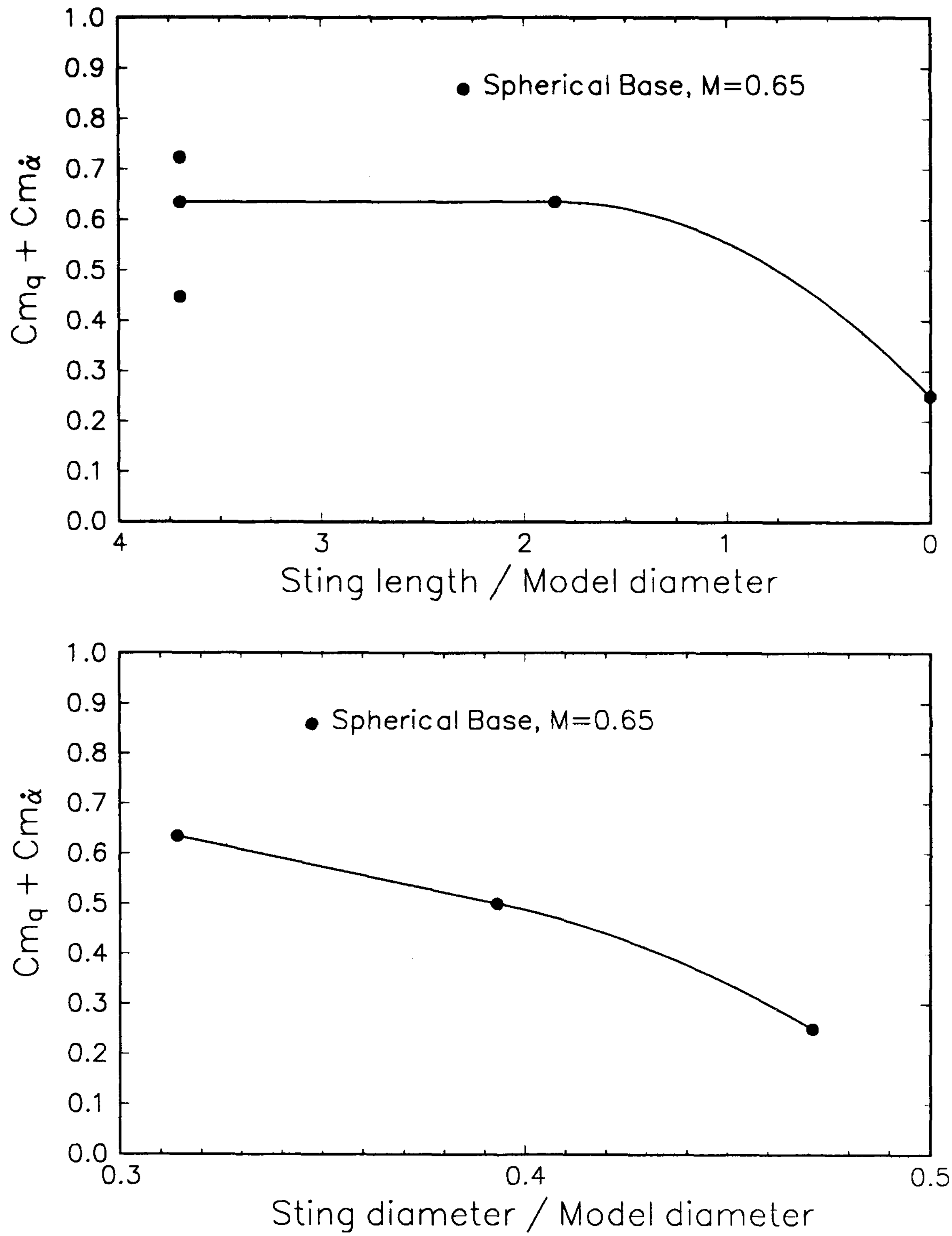


Figure 20 *Dynamic Sting Effects on Spherical-based Re-entry Bodies (modified from Reference* [52]*)*

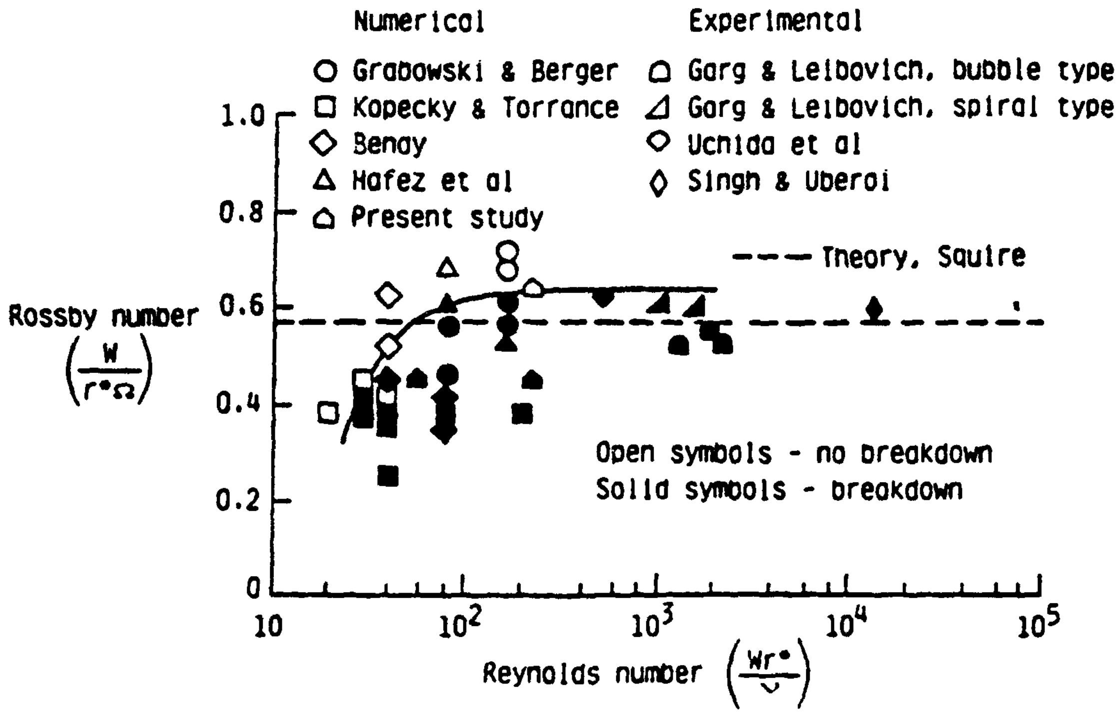


Figure 21 *The Relationship between Rossby Number and Reynolds Number for Wing-Tip Vortices (reproduced from Reference [63])*

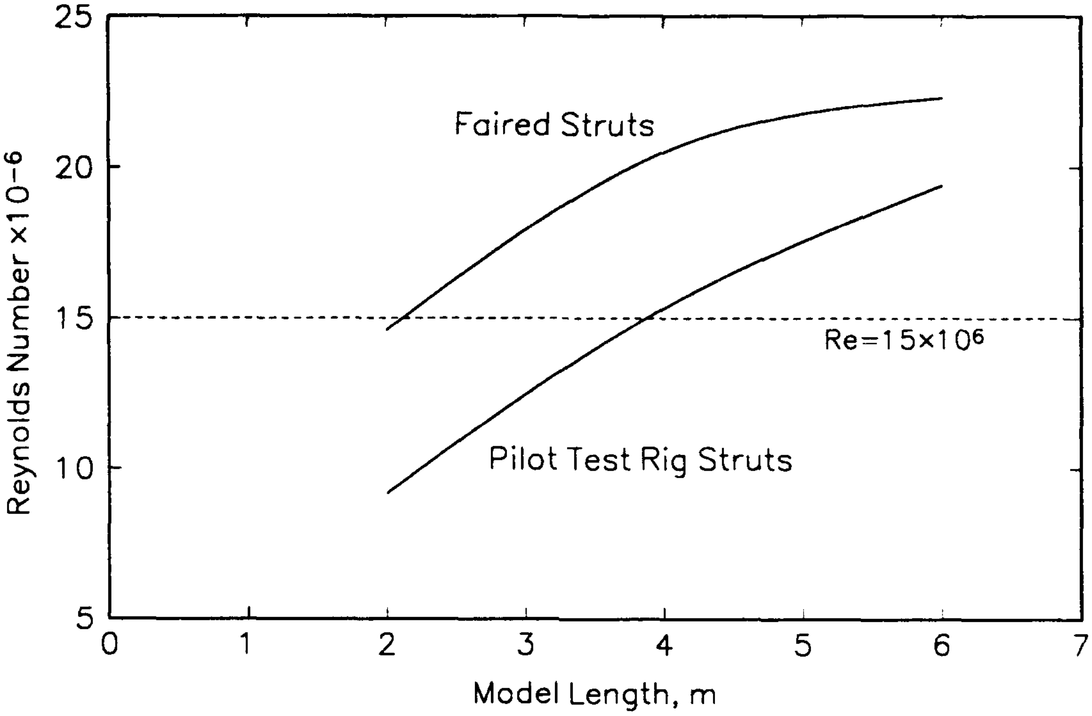


Figure 22 *Achievable Reynolds Number limited by Strut Drag (reproduced from Reference [3])*

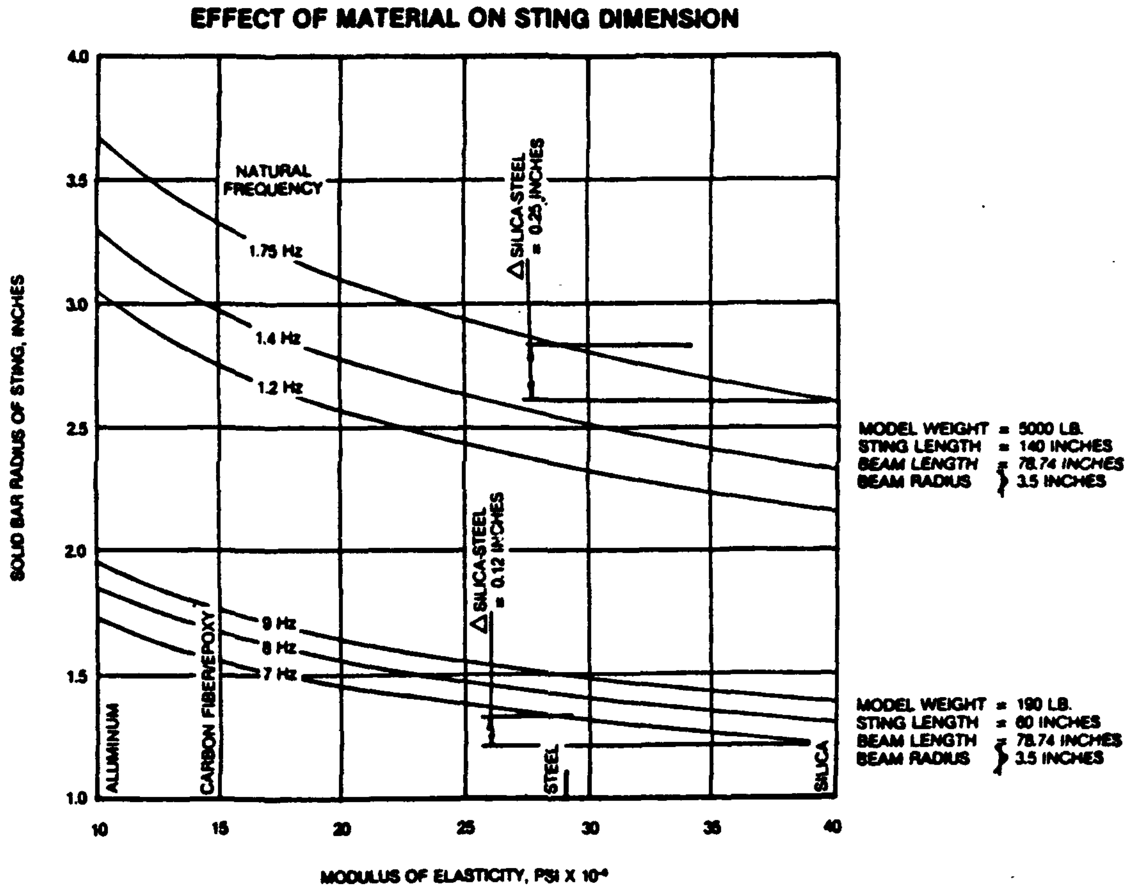


Figure 23 *Sting Material Parametric Study (reproduced from Reference [47])*

Appendix A: Finite Element Analysis of the MDTF Pilot Model Sting

A.1 Background

As noted in Section 5.2, a finite element analysis was made of the MDTF pilot model sting to determine why it exhibited excessive bending and an unexpectedly low natural frequency in the static frame evaluation at Canadair [3]. The analysis was done by Neil Pegg, Group Leader for Structural Mechanics, DREA, using a simple beam model in DREA's finite element code VAST.

A schematic of the sting and beam assembly is sketched in Figure A.1. These components are actually much more slender; their correct proportions can be seen on Figure 8. The sting is an axisymmetrical unit machined from MT 1015 steel tube with 3 inch o.d. and 1 inch i.d. The sting is supported at each end of the box beam. From the measurements and analysis discussed in this appendix, it can be inferred that the sting design criteria were applied only to that portion ahead of the forward strut; ie: the sting was assumed to be cantilevered from ground at the forward strut, as sketched in Figure A.2a.

Reviewing this arrangement in light of the test results, it was concluded that in reality the sting is effectively pinned at each end of the box beam as sketched in Figure A.2b. The different natural frequencies and stiffnesses associated with these alternatives can be estimated from finite element analysis of the sting alone, without the necessity of modeling the beam. Figure A.2c illustrates the option of additional pinning to increase the natural frequency.

A.2 Results

Deflection of the pinned model under static load was calculated for initial verification and to demonstrate that stiffness was correctly represented. Under a load of 4430 N the deflection was measured at 44.4 mm [3] and calculated to be 46.5 mm. Such close agreement was satisfactory on both counts.

Natural frequencies were estimated for the three configurations shown in Figure A.2 with the modification that the grounded sting case was approximated by clamping the sting at each end of the box beam. The submarine model was represented as a point mass at the end of the sting. The calculations were done for the sting in air, and in water accounting for the added masses and for a flooded model. Natural frequencies in Hz are listed in the following table:

		in air	in water
Target value			5.0
Measured value		6.4	2.8
Calculated:	(a) clamped	10.8	5.7
	(b) 2 pins	7.2	3.9
	(c) 3 pins	8.8	4.6

Calculated values for the two pin model, the sting pinned at each end of the beam, fell between

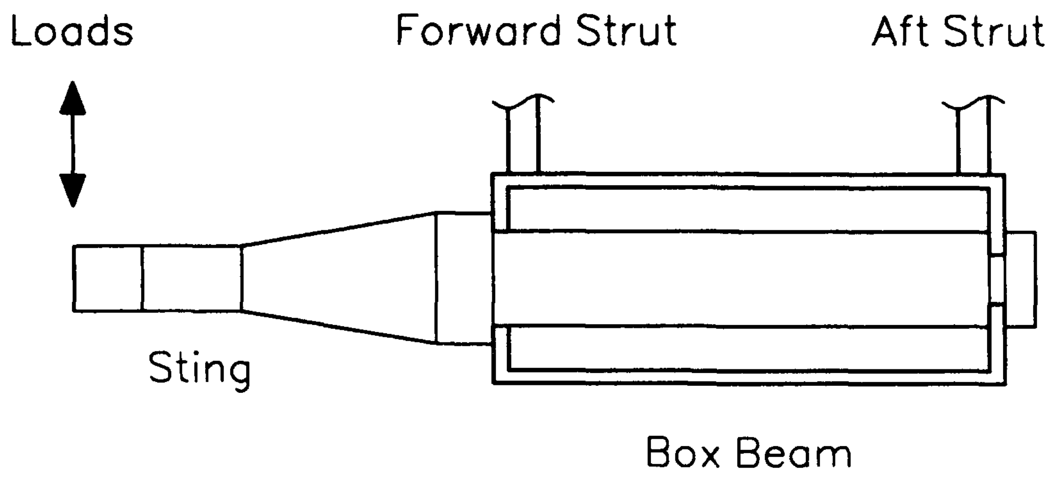
the measured and target values. We would normally expect much better agreement with measurements if the problem were so simple, so there must be additional reasons for this discrepancy such as flexibility in the beam or strut assemblies which was not modeled, or additional added mass effects which could not be determined.

Clamping the sting, approximating the arrangement of Figure A.2a, raises the calculated natural frequency by nearly 2 Hz and brings it above the target value. The measured natural frequencies are clearly more consistent with the sting being pinned, rather than clamped, to each end of the beam.

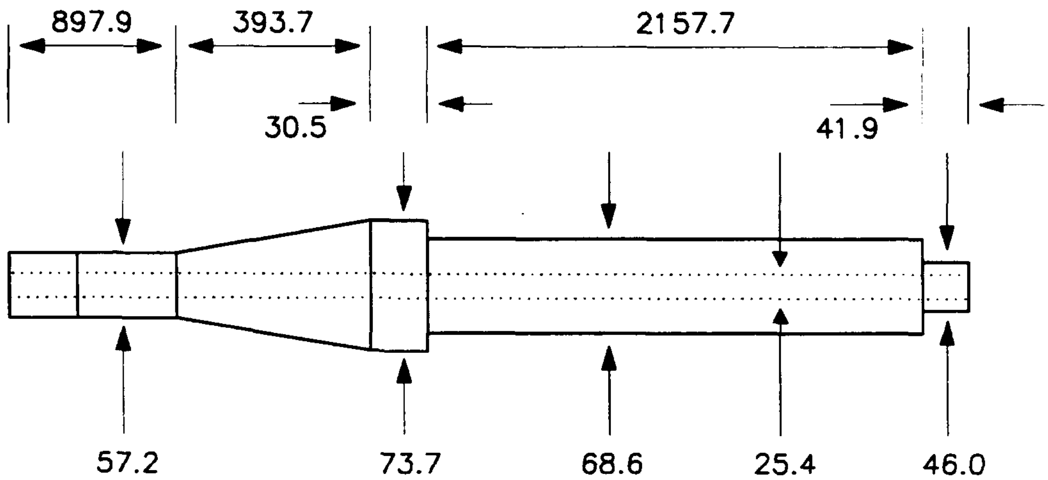
It is not intended to modify the present arrangement but to gain knowledge for the redesign of these components as part of procurement. However, the 3 pin arrangement sketched in Figure A.2c represents a quick-fix that could be easily made. The calculation shows an increase of 0.7 Hz in the natural frequency, which is significant. This suggests that the target value could be reached by the addition of some additional pinning points within the beam.

A.2 Conclusions from this Study

The pilot model MDTF sting is effectively pinned, rather than clamped, at each end of the box beam. As a consequence, there are excessive deflections under load and vibrational modes with unexpectedly low natural frequencies. Additional pinning within the box beam would be a relatively straightforward way of alleviating this problem in the present arrangement, but it is more important to take account of this behavior in redesigning the sting/beam assembly for procurement of the production MDTF.

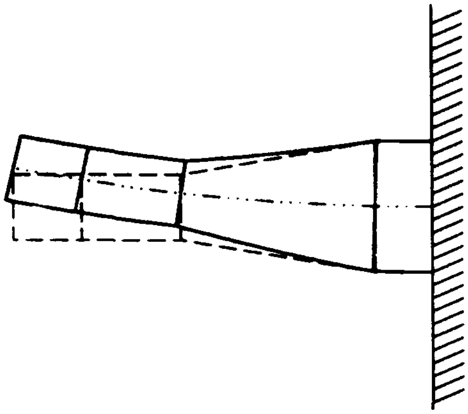


a) Installation

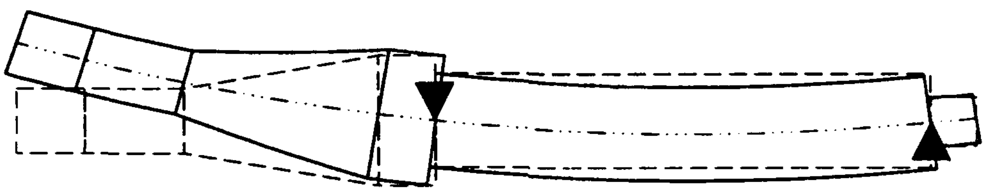


b) Sting Dimensions in mm (not in proportion)

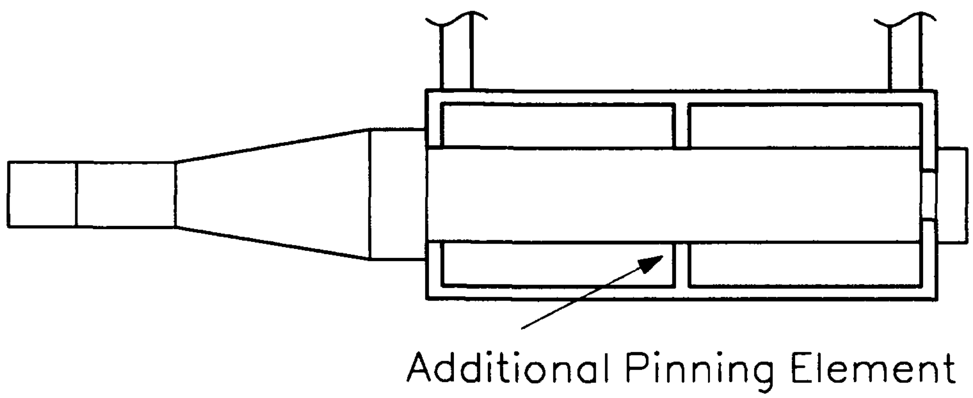
Figure A.1 *MDTF Sting Schematic*



a) *Grounded Bending Mode*



b) *Two Pin Model Bending Mode*



c) *Additional Pinning*

Figure A.2 *MDTF Sting — Bending Modes and Additional Support Option*

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The literature on model testing with a tail sting support was reviewed for its application to submarine experiments on the Marine Dynamic Test Facility (MDTF) proposed for the Institute for Marine Dynamics, St. John's, Newfoundland. A number of flow mechanisms for both static and dynamlic sting interference are discussed in this context, but because of the unique features of the MDTF their relevance is not always clear-cut. Other sting-related issues such as deflection under load and vibration are briefly discussed. It is concluded that sting support for large submarine models on the MDTF is feasible for acceptable levels of interference without elaborate correction procedures. Some recommendations are made for MDTF implementation.

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